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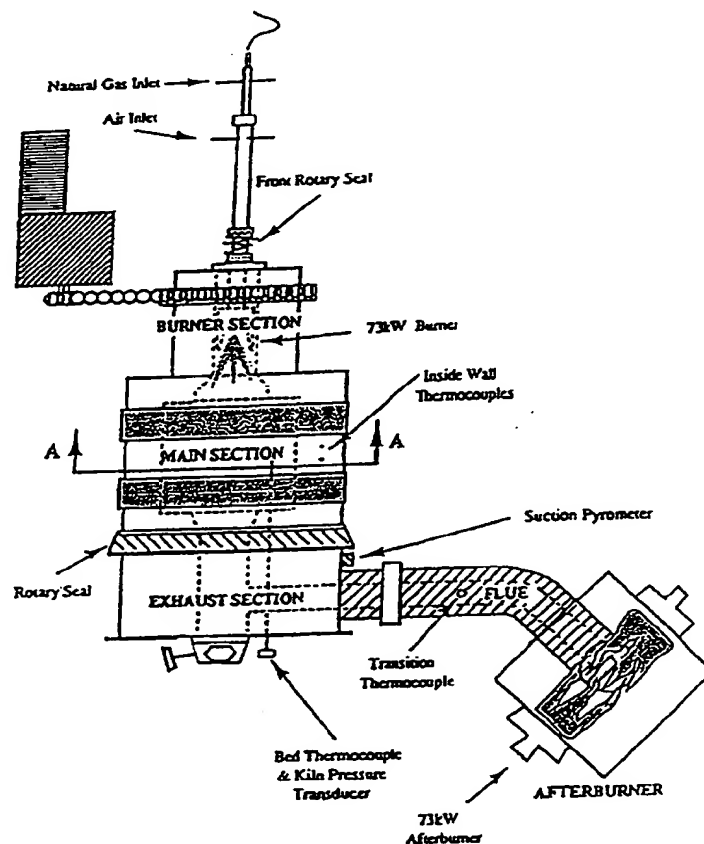


## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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<b>(21) International Application Number:</b> PCT/US96/12008 <b>(22) International Filing Date:</b> 19 July 1996 (19.07.96)  <b>(30) Priority Data:</b> 60/001,337                      21 July 1995 (21.07.95)                      US  <b>(71) Applicant (for all designated States except US):</b> UNIVERSITY OF UTAH RESEARCH FOUNDATION [US/US]; 210 Park Building, Salt Lake City, UT 84112 (US).  <b>(72) Inventors; and</b> <b>(75) Inventors/Applicants (for US only):</b> GAO, Dachun [CN/US]; 3212 East 3900 South, Holladay, UT 84124 (US). SILCÔX, Geoffrey, D. [US/US]; 730 North Hilltop Road, Salt Lake City, UT 84103 (US).  <b>(74) Agents:</b> BOND, Laurence, B. et al.; Trask, Britt & Rossa, P.O. Box 2550, Salt Lake City, UT 84110 (US).		<b>(81) Designated States:</b> CA, JP, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).  <b>Published</b> With international search report.

**(54) Title:** MULTICOLOR OPTICAL PYROMETER**(57) Abstract**

A method of using multiple single-color pyrometers to correct for the effects of reflected radiation when optically measuring the temperature of a relatively cool surface in hotter surroundings is disclosed. The method includes obtaining pyrometric readings from the surface at two or more wavelengths and thereafter utilizing the readings together with the emissivity of the surface to calculate the surface temperature. In one version of the method the emissivity of the surface being measured is determined by a method which includes heating the surface in an insulated environment and thereafter obtaining readings pyrometrically from the surface once the insulation of the surface is removed. The readings are then utilized to calculate the emissivity by extrapolating the readings to a time zero. In those versions of the method which utilize pyrometric readings taken over three or more wavelengths, emissivity may be calculated through the use of relevant mathematical expressions.



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## MULTICOLOR OPTICAL PYROMETER

BACKGROUND OF THE INVENTION

5        Technical Field: The invention relates to optical measurement. The invention is specifically directed to the measurement of temperatures using infrared technology.

Statement of the Art: There are many applications of radiation thermometers throughout the industrial world. The first modern attempt at radiation thermometry  
 10        dates as far back as 1828 (Dike et al., 1966). The first comprehensive treatment of the theory of radiation thermometry and its practice was published in 1960 by Thomas R. Harrison (1960). Since then, many of the most important advances in this field have been described and chronicled in volume 4 and 5 of the well-known proceedings, *Temperature, its Measurement and Control in Science and Industry*, a  
 15        series of symposia beginning in 1929. More recently, DeWitt and Nutter (1988) have provided a comprehensive coverage of the principles and applications of radiometric methods for measuring surface temperature.

      The following U.S. Patents have been identified as identifying representative efforts in this area: 3,619,059; 3,454,769; 4,020,695; 4,818,102; 5,029,117;  
 20        5,125,739; 5,226,732; 5,231,595; 5,318,362; 5,326,173.

      Ono (1988) and Nutter (1972) cover a number of previous investigations to cope with the extraneous radiation caused by hotter surroundings and with uncertain emissivities.

      Atkinson and Strange (1976) developed a technique using a fiber pyrometer  
 25        probe with two identical silicon diode detectors to measure the temperature of turbine blades in the presence of reflected energy originating from the flame. The spectral bands they chose were 0.4 -1.2  $\mu\text{m}$  (as received or unfiltered) and 0.4-0.85  $\mu\text{m}$  (filtered). Note that the latter range overlaps with the former. They described their system with the following equations

$$30 \quad E_{1,\text{total}} = \int_0^\infty S_1(\lambda)P(T_b)d\lambda + C_r \int_0^\infty S_1(\lambda)P(T_r)d\lambda$$

$$E_{2,\text{total}} = \int_0^\infty S_2(\lambda)P(T_b)d\lambda + C_r \int_0^\infty S_2(\lambda)P(T_r)d\lambda$$

(A)

      where  $E_{1,\text{total}}$  is the reading of the pyrometer,  $T_b$  and  $T_r$  are the blade temperature and the reflected source temperature;  $S_i(\lambda)$  is the sensitivity of pyrometer  $i$  at

-2-

wavelength  $\lambda$ ;  $P(T)$  is the monochromatic emissive power of a blackbody at temperature  $T$  and  $C_r$  is a complex, constant term that includes the effects of the emissivity of the surface, the emissivity of the gas, and geometrical considerations of reflected radiation.

- 5 The investigators assumed  $S_i(\lambda)$  could be pre-determined from calibration studies and from knowing the spectral sensitivity of the detectors. They further assumed  $T_r$  was measured or was estimated from the general characteristics of flames in turbine engines. Then only two variables, namely  $T_b$  and  $C_r$ , were left as unknowns in the two expressions of equation (A). A trial and error method  
10 involving graphical analysis was used in an attempt at obtaining the blade temperature.

- Some of the assumptions in this study are questionable. The authors treated the turbine blade as a blackbody on the basis of the nearly isothermal conditions within the engine (therefore no emissivity factors were needed in the first terms of  
15 the equation (A) relating to blade temperature,  $T_b$ ). An extremely hot flame  $2148^\circ\text{C}$  ( $3900^\circ\text{F}$ ) was assumed as the reflected energy source and the temperature difference between the leading edge of the blade and body of the blade was taken as  $220^\circ\text{C}$  ( $400^\circ\text{F}$ ). The reliability of using the same  $S_i(\lambda)$  for both  $T_b$  and  $T_r$  is also doubtful.

- 20 DeWitt (1986) reviewed and commented on the similar work by Imgram and McCanless (1983) which aimed at determining the surface temperature of tubes in a crude oil refinery heater. By sighting through a peephole, the radiation thermometer viewed a portion of the tube, and the problem was to relate the pyrometer signals to the true tube wall surface temperature. The mathematical  
25 system was given as

$$\begin{aligned} E_{\lambda 1}(T_{\lambda 1}) &= \varepsilon_{\lambda 1} E_{\lambda 1,b}(T_s) + F_{w \rightarrow i}(1 - \varepsilon_{\lambda 1}) E_{\lambda 1,b}(T_{w1}) + (1 - F_{w \rightarrow i})(1 - \varepsilon_{\lambda 1}) E_{\lambda 1,b}(T_{f1}) \\ E_{\lambda 2}(T_{\lambda 2}) &= \varepsilon_{\lambda 2} E_{\lambda 2,b}(T_s) + F_{w \rightarrow i}(1 - \varepsilon_{\lambda 2}) E_{\lambda 2,b}(T_{w2}) + (1 - F_{w \rightarrow i})(1 - \varepsilon_{\lambda 2}) E_{\lambda 2,b}(T_{f2}) \end{aligned} \quad (\text{B})$$

- where  $F_{w \rightarrow i}$  is the view factor between the furnace wall and the target surface,  $T_{wi}$  is  
30 the wall temperature of the furnace, and  $T_{fi}$  is the temperature of the flame.  $T_{wi}$  and  $T_{fi}$  were determined optically. The emissivities,  $\varepsilon_{\lambda 1}$  and  $\varepsilon_{\lambda 2}$ , were known from other measurements.

Wavelengths of  $0.9\ \mu\text{m}$  and  $3.9\ \mu\text{m}$  were used and the emissivity of the surface of the tube was 0.9 for both  $\lambda_1$  and  $\lambda_2$ . Table 1 shows the results obtained (Dewitt, 1986). The  $T_f$ 's and  $T_w$ 's were measured optically at  $0.9$  and  $3.9\ \mu\text{m}$ .

Tube surface temperatures,  $T_{\lambda_i}$ , which included the reflected components, were also measured in the same manner at two locations (one was closer to the flame and the other is closer to the wall). The true surface temperature of the tubes,  $T_s$ , and the view factor,  $F_{w-t}$ , were calculated from equations (B). The differences between the optically measured temperatures and the calculated temperatures,  $T_{\lambda_i} - T_s$ , in different locations and at different wavelengths, are also tabulated.

Table 1 Measurements in a direct-fired, crude oil refinery heater (Dewitt, 1986).

	$T_{\lambda_i}, ^\circ\text{C}$		$T_s, ^\circ\text{C}$	$T_{w-t}$	$T_{\lambda_i} - T_s, ^\circ\text{C}$	
	$0.9\ \mu\text{m}$	$3.9\ \mu\text{m}$			$0.9\ \mu\text{m}$	$3.9\ \mu\text{m}$
Flame Temp, $T_f$	1521	1293				
Wall Temp, $T_w$	966	943				
Tube Temp						
Closer to flame	1021	907	888	0.71	133	19
Closer to wall	979	882	868	0.81	111	14

Without other supporting observations (temperature and flow rate of the process fluid in the tubes, thermocouples at the target, etc.), it was not possible to assess the accuracy of the method (Dewitt, 1986). First, the calculated view factor from wall to target ( $F_{w-t}$ ) was lower if the target was in closer proximity to the burner. This is reasonable because the view factor from flame to target is  $(1 - F_{w-t})$  by the summation rule. Second, the reflection errors,  $(T_{\lambda_i} - T_s)$ , are less at  $3.9\ \mu\text{m}$  than at  $0.9\ \mu\text{m}$ , which shows that the longer wavelength pyrometer is less sensitive to the reflected radiation. The errors also increase if the target is closer to the flame in agreement with the concept that errors are mainly caused by the reflected component originating from the flame.

The most questionable deficiency in the above system is the use of  $T_{w_i}$  as the true wall temperature even though it was determined by a pyrometer. The errors caused by the reflected radiation from the flame in  $T_{w_i}$  are comparable to the errors in  $T_s$ , and therefore should not be ignored. Moreover, the simplifying assumptions

(particularly through the use of a view factor) severely limit this method (Dewitt, 1986).

The work done by Suarez-Gonzalez et al. (1987, 1992) also relates, in principle, to previous pyrometry approaches. It is the most recent technique published which discusses measurement of a surface temperature in the presence of hotter surroundings. The problem is again the measurement of the temperature of turbine blades in a jet engine. The spectral bands in the two-color system were similar to what Atkinson and Strange (1976) used, 0.4 to 1.05  $\mu\text{m}$ , unfiltered, and 0.4 to 0.85  $\mu\text{m}$ , filtered. The spectral bands used in their three-color system were a short wavelength band at 0.3 to 0.85  $\mu\text{m}$ , a middle wavelength band at 0.85 to 1.0  $\mu\text{m}$ , and a long wavelength band at 1.0 to 1.8  $\mu\text{m}$ .

For the two-color system, the unfiltered and filtered signals  $E_u$  and  $E_f$  were produced from the pyrometer targeting the turbine blade. The pyrometer signals,  $E_u$  and  $E_f$ , were the sums of emitted and reflected components.

$$\begin{aligned} E_u &= E_{ub} + E_{ur} \\ E_f &= E_{fb} + E_{fr} \end{aligned} \quad (C)$$

The ratio between the filtered and unfiltered signals for a given reflected intensity was assumed constant

$$E_{ur} / E_{fr} = \text{constant} = R_{uf} \quad (D)$$

Consequently, the equation for the total unfiltered signal was written as

$$E_u = E_{ub} + R_{uf} E_{fr} \quad (E)$$

From equation (C), the filtered, reflected signal becomes

$$E_{fr} = E_f - E_{fb} \quad (F)$$

Combining the preceding two equations results in

$$E_u - R_{uf} E_f = E_{ub} - R_{uf} E_{fb} \quad (G)$$

where, if  $R_{uf}$  is known, the left-hand side is a function of detectable optical signals (including components from both the blade and the flame), while the right-hand side is only a function of blade temperature.



Since the flame (blackbody) temperature can be estimated on the basis of material and energy balances, and  $R_{ur}$  can be calculated from equation (D), the term  $(E_u - R_{ur}E_r)$  in the left-hand side of equation (G) is then obtained from the pyrometer readings. As a result, the blade temperature can be calculated since a monotonic  
5 relationship exists between  $(E_{ub} - R_{ur}E_{rb})$ , which is equal to  $(E_u - R_{ur}E_r)$  by equation (G), and  $T_b$ , within a realistic blade temperature range ( $< 1650^\circ\text{C}$ ). Here the emissivity of the blade and the effect of the engine geometry are considered known. The central idea of this approach is to reduce the two equations (C) to one equation (G) in order to establish the relationship between the pyrometer readings (their  
10 combination, actually) and the blade temperature,  $T_b$ . As a result, only one unknown,  $T_b$ , can be solved for.

On the basis of the two-color system, a three-color system also was developed. Two combinations, short-middle wavelength bands and middle-long wavelength bands were separately used in the same way as equations (C) through  
15 (G). Hence, this three-color system essentially included two, two-color systems and therefore allowed two variables,  $T_b$ , and the flame temperature,  $T_f$ , to be measured. Unlike being specified based on the estimated flame temperature, as was done for  $R_{ur}$  in the two-color system,  $R_{sm}$  and  $R_{ml}$  were now calculated based on a given  $T_f$ . If  $T_f$  was not properly chosen, the resulting incorrect values of  $R_{sm}$  and  $R_{ml}$  would  
20 give different blade temperatures by the two systems, which is not realistic. The value of  $T_f$  (and then  $R_{sm}$  and  $R_{ml}$ , accordingly) can be chosen iteratively until the difference in the  $T_b$ 's from the two systems becomes acceptably small.

The most severe limitation of the systems proposed by Suarez-Gonzalez et al. is the need for a specified emissivity of the surface. This emissivity is used to  
25 obtain the relationship between the temperature of the blade,  $T_b$ , and the pyrometer signals originating from the blades,  $E_b$ . It is also used to obtain the relationship between the temperature of the flame,  $T_f$ , and the reflected signals,  $E_{ur}$  and  $E_{fr}$ . The requirement of a emissivity prevents this technique from being used in many applications where the emissivity of the surface is not known.

30 Measurement of surface temperature has many industrial applications. For example, temperature measurement of particles in a furnace may prove very beneficial in controlling the operation of the furnace. As an example, the temperature of the slumping beds of solids in rotary kilns is a key parameter in

hazardous waste incineration. However, direct bed temperature measurement in full-scale rotary kilns is difficult due to the rotation of the kiln and the harshness of the kiln environment.

Because of this, an indirect approach is frequently applied in which the temperature of the kiln combustion gases is measured and used to control the kiln's operating conditions. It is assumed that the bed solids' temperature is maintained within normal limits, if the proper combustion gas temperature range is maintained. This approach is not as attractive as a direct measurement of the solids' temperature, especially if the solids' temperature can be directly measured a significant distance before the solids exit the kiln. Direct, upstream measurements increase the possibility of actually altering kiln conditions to correct inappropriately cool solids temperatures before the solids leave the kiln.

One possible technique for direct measurement is infrared optical pyrometry. At first glance this appears to be a feasible technology if air purging can keep lenses clean and water cooling can prevent the electronics from overheating (Andreyuk, 1989); however, an optical method might not obtain the true bed temperature for the following reasons:

- A) The wavelengths selected for optical measurements must avoid the principle absorption and emission bands of the major kiln gas species such as H<sub>2</sub>O and CO<sub>2</sub>.
- B) An infrared pyrometer measures the radiation intensity from a surface which is the sum of emitted and reflected components. If a relatively cool surface is placed in hot surroundings, then the reflected component of the intensity will cause the temperature to be overestimated.
- C) The sight path of the pyrometer might be obscured by small, suspended particles such as soot, entrained fines, and smoke, therefore the optically determined temperatures will involve errors.

Conventional pyrometers are not able to correct for the effects of reflected radiation from the surface of interest. This interference results in apparent surface temperatures that are too high.

### DISCLOSURE OF THE INVENTION

A method of using multiple single-color pyrometers to correct for the effects of reflected radiation when optically measuring the temperature of a relatively cool surface in hotter surroundings is disclosed. This technique requires that the  
5 emissivity of the surface be known.

The multicolor pyrometer measures the intensity of radiation leaving a surface over two or more narrow wavelength bands. The intensities permit the calculation of the surface's temperature, the effective temperature of the surroundings, and in some cases the emissivity of the surface.

10 The invention differs from the pyrometric techniques previously available in its ability to discriminate between reflected and emitted radiation. The method obtains measurements of detected radiation at different wavelengths and then by solving simultaneous equations relating the unknowns determines the temperature of a surface. In the version of the method which utilizes two-color pyrometric  
15 measurements, the emissivity of the surface being measured must be independently determined or otherwise known. In the three-color approach, the surface emissivity is a third unknown which is solved for along with the surface temperature and the effective surrounding's temperature. The three-color method does not require the calculation of surface emissivity when measurements at three wavelengths are  
20 utilized and the surface is grey over the wavelength range of the measurement.

Applications include the measurement of the temperature of the clinker exiting cement kilns and the temperature of the solids exiting solid hazardous waste incinerators.

In conjunction with the multicolor system, a new method is disclosed to  
25 measure the spectral, surface emissivity of porous materials. This method involves heating a sample of the material to a uniform temperature and then suddenly exposing it to cool surroundings. Knowing the initial temperature and the optically measured brightness temperature enables the calculation of the emissivity. This technique requires that the pyrometer readings be extrapolated back to time zero.

30 The application of the multicolor techniques to industrial applications, such as measuring the temperature of particles, e.g., solids in furnaces and, in particular, to incinerators, is complicated by the presence of soot and dust, and by wide variations in the types of surfaces present. Experimental results using the two-color

approach indicate that interferences from smoke, soot, and dust can have significant effects on pyrometer readings. Pyrometers operating at longer wavelengths are less sensitive to these interferences.

While a two-color method is disclosed in extensive detail the methodology of that method has been extended to a novel, three-color technique which is applicable even when the emissivity of the surface is unknown, provided that the emissivity is independent of wavelength over the range of wavelengths being used. That is, this new method requires that the three spectral surface emissivities are the same. Computer simulations show that the three-color system is a promising method.

The three-color technique requires properly selected wavelengths. The system is highly sensitive to errors in the individual pyrometer readings if the errors are not in the same direction and are not of roughly the same magnitude. The three-color system is less sensitive to errors which are in the same direction and of approximately the same magnitude. A detailed sensitivity analysis indicates that it is theoretically favorable to design and fabric a three-color system which uses only one lens/sensor-amplifier-display system for the three-spectral signals. Further analysis suggests that the sensitivity to errors can be reduced 5-20 fold if the signals from the instrument are not processed into brightness temperatures, but are used directly in the calculation of the temperatures and emissivity.

#### BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 schematically depicts emitted and reflected components of radiation detected by an optical pyrometer.

FIG. 2 schematically depicts a cross section of the 1.8 kW furnace for emissivity determination showing the oxidized Cu plate with two thermocouples inserted for temperature measurement.

FIG. 3 schematically depicts a device used to measure the spectral emissivity of sand or clay. The insulating cover is quickly removed and the transient temperature of the sample is measured optically.

FIG. 4 schematically depicts the top view of the water-cooled sample tray with two thermocouples to estimate the copper plate surface temperature.

FIG. 4A schematically depicts the same sample tray as FIG. 4 further illustrating that the same tray can be used for sand or clay.

-8/1-

FIG. 4B schematically depicts a side view of the water-cooled sample tray of FIG. 4. The figure in the circle shows that the same tray can be used for sand or clay.

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FIG. 5 schematically depicts a rotary kiln simulator.

FIG. 5A is a cross sectional view of FIG. 5 taken along section lines A-A.

FIG. 6 is a schematic of optical measurement of spectral, brightness surface temperature by two single-color pyrometers.

5        FIG. 7 is a graph depicting the normal, spectral emissivities of oxidized copper plate at 1.05 and 2.2  $\mu\text{m}$ .

FIG. 8 is a graph depicting oxidized copper data for two-color pyrometer verification.

10       FIG. 9 is a graph depicting the normal, spectral emissivity of sand at 1.05 and 2.2  $\mu\text{m}$ .

FIG. 10 is a graph depicting the normal, spectral emissivity of Smokey Joe clay at 1.05 and 2.0  $\mu\text{m}$ .

15       FIG. 11 is a graph depicting temperature data from water cooled tray test in rotary kiln. The thermocouple solids' temperature is measured 1.5 mm below the surface of the sand.

FIG. 12 is a graph depicting the optical measurement results at batch, transient conditions in the kiln using sand at 2 rpm rotation rate and 5% fill fraction.

20       FIG. 13 is a graph depicting an illustrative example of the spectral, brightness temperature measurement at the surface temperature 1234°F. The brightness temperatures and the surface temperature then can be used to calculate the spectral emissivity.

FIG. 14 are bar graphs depicting sensitivity analysis for errors in pyrometer reading for a surface with an emissivity of 0.9.

25       FIG. 15 are bar graphs depicting sensitivity analysis for errors in pyrometer reading for a surface with an emissivity of 0.3.

FIG. 16 are bar graphs depicting sensitivity analysis for errors in emissivity for a surface with an emissivity of 0.9.

30       FIG. 17 are bar graphs depicting sensitivity analysis for errors in emissivity for a surface with an emissivity of 0.3.

FIG. 18 is a graph depicting the effects of smoke interference to a 1.05  $\mu\text{m}$  pyrometer reading for an oxidized stainless steel plate outsider of the kiln at an approximate temperature of 1150°F.

-9/1-

FIG. 18A is a graph depicting the effects of smoke interference to a 2.2  $\mu\text{m}$  pyrometer reading for an oxidized stainless steel plate outsider of the kiln at an approximate temperature of 1150°F.

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FIG. 19 is a graph depicting soot interference effects at an acetylene flow rate of 11.0 SCFH.

FIG. 20 is a graph depicting entrained fines interference effects when the clay particles are fed at a mass flow rate of 62.5 g/min.

5        FIG. 21 is contour chart of brightness temperatures,  $T_{B\lambda 1}$  and  $T_{B\lambda 2}$ , corresponding to the surface temperature and the effective surrounding temperature,  $T_{surf}$  and  $T_{surr}$ . The conditions are  $\lambda_1 = 1.05 \mu\text{m}$ ,  $\lambda_2 = 2.2 \mu\text{m}$ , and  $\varepsilon_{\lambda 1} = 0.3$ ,  $\varepsilon_{\lambda 2} = 0.4$ . The plain numbers and lines are for  $T_{B\lambda 1}$  and the bold ones are for  $T_{B\lambda 2}$ .

10        FIG. 22 is a contour chart of  $T_{surf}$  as a function of the brightness temperatures,  $T_{B\lambda 1}$  and  $T_{B\lambda 2}$ .

FIG. 22A is a contour chart of  $T_{surr}$  as a function of the brightness temperatures,  $T_{B\lambda 1}$  and  $T_{B\lambda 2}$ .

15        FIG. 23 is a graph which illustrates the effect of errors in the brightness temperature at  $0.8 \mu\text{m}$  on the temperatures of the emissivity. No errors are associated with the other wavelengths.

FIG. 23A is a graph which illustrates the effect of errors in the brightness temperature at  $0.8 \mu\text{m}$  on the temperatures of the surface and the surroundings. No errors are associated with the other wavelengths.

20        FIG. 24 is a graph which depicts the effect of errors in the brightness temperature at  $1.6 \mu\text{m}$  on the emissivity. No errors are associated with the other wavelengths.

FIG. 24A is a graph which depicts the effect of errors in the brightness temperature at  $1.6 \mu\text{m}$  on the temperatures of the surface and the surroundings. No errors are associated with the other wavelengths.

25        FIG. 25 is a graph which illustrates the effect of errors in the brightness temperature at  $2.2 \mu\text{m}$  on the emissivity. No errors are associated with the other wavelengths.

30        FIG. 25A is a graph which illustrates the effect of errors in the brightness temperature at  $2.2 \mu\text{m}$  on the temperatures of the surface and the surroundings. No errors are associated with the other wavelengths.

FIG. 26 is a graph which depicts the partial derivative,  $\partial T_{surf}^* / \partial T_{B\lambda i}^*$ ,  $i=1, 2, 3$ , as a function of the normalized brightness temperature with errors in the brightness temperature of  $j=0, 1, \dots, 6$ .



-10/1-

FIG. 27 is a graph which depicts the partial derivative,  $\partial T_{\text{surf}}^* / \partial T_{\text{B}\lambda i}^*$ ,  $i=1, 2, 3$ , as a function of the normalized brightness temperature with errors in the brightness temperature of  $j=0, 1, \dots, 6$ .

FIG. 28 is a graph which depicts the partial derivative,  $\partial \varepsilon^* / \partial T_{\text{B}\lambda i}^*$ ,  $i=1, 2, 3$ , as a function of the normalized brightness temperature with errors in the brightness temperature of  $j=0, 1, \dots, 6$ .

FIG. 29 is a graph which illustrates that Type A error in the brightness temperature errors in three-color results are relatively insensitive to errors of Type A which appear on all three pyrometers with the same magnitude and sign. The scale of normalized error in the brightness temperature is also shown on the top of the group.

FIG. 29A is a graph illustrating normalized Type A error in brightness temperature.

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FIG. 30 is a graph illustrating the relationship between the derivatives,  $dT_{B\lambda}^*/dR_{\lambda}^*$  and the normalized radiosity of the three-color system. The small values of the derivatives indicate that skipping the conversion of  $R_{\lambda}$  to  $T_{B\lambda}$  decrease the sensitivity to errors.

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### BEST MODE OF THE INVENTION

It is now known that heat is a form of energy which is transferable from one material to another by either conduction, convection, or radiation. All materials, at all temperatures, down to near absolute zero, radiate electromagnetic energy. The wavelengths at which this radiation occurs depends on the nature and temperature of the material. The temperature of the material determines both the quantity and the wavelengths of energy radiated. As the temperature increases, the wavelengths shift to shorter values. In combustion applications, the bulk of the thermal radiation occurs in the infrared (2-20  $\mu\text{m}$ ) and near infrared (0.7-2  $\mu\text{m}$ ) ranges. Therefore, the optical devices that measure the intensities of thermal radiation are often referred to as infrared radiation thermometers (pyrometers).

The theory of optical pyrometers is based on the Planck distribution,

$$E_{b\lambda} = C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} \quad (1)$$

This expression relates the amount of energy emitted by a perfect radiator (blackbody) per unit wavelength, per unit of time, per unit area, at wavelength  $\lambda$ , to the temperature of the radiator,  $T$ . The values of the radiation constants,  $C_1$  and  $C_2$ , are  $3.742\text{E}10^8 \text{ W}\cdot\mu\text{m}^4/\text{m}^2$  and  $1.439\text{E}10^4 \mu\text{m}\cdot\text{K}$ .

The Planck law reduces to equation (2), called the Wien equation, which is accurate to within 1 percent when  $\lambda T$  is less than  $3000 \mu\text{m}\cdot\text{K}$ :

$$E_{b\lambda} \approx C_1 \lambda^{-5} e^{-C_2/\lambda T} \quad (2)$$

This range is applicable for the instant method. Because of internal reflection at the surface of a material, the intensity of the radiation passing through a surface, and thus emitted, is less than that given by equation (2). For a nonblackbody, equation (2) becomes

$$E_{\lambda} = \varepsilon_{\lambda} C_1 \lambda^{-5} e^{-C_2/\lambda T} = \varepsilon_{\lambda} E_{b\lambda} \quad (3)$$

where  $\epsilon_\lambda$  the emissivity which is between 0 and 1. equation (3) can also be written using a fictitious temperature,  $T_{B\lambda}$  called the brightness temperature. This is the temperature at which a black body will emit the same amount of energy as a surface with emissivity  $\epsilon_\lambda$  and true temperature  $T$ :

$$E_\lambda = C_1 \lambda^{-5} e^{-C_2/\lambda T_{B\lambda}} \quad (4)$$

If the emissivity is independent of wavelength (gray) or does not change significantly over the selected wavelength range, then equation (3) gives

$$E_{\lambda_1} / E_{\lambda_2} = (\lambda_2 / \lambda_1)^5 e^{-\frac{C_2}{T} \left( \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \right)} \quad (5)$$

which means that the temperature can be determined in spite of the fact that the emissivity may not be known.  $E_{B\lambda}$  can be calculated using equation (1) or (2). A single-color pyrometer can be used to determine the surface brightness temperature,  $T_{B\lambda}$ , and then  $E_\lambda$  can be calculated using equation (4). The ratio of  $E_\lambda$  to  $E_{B\lambda}$ , as shown in equations (3) and (4), is  $\epsilon_\lambda$ . The combination of one radiation ratio thermometer and one single-color pyrometer can, in principle, be used to determine the emissivity of the surface.

Radiation originating from extraneous sources and reflecting from the surface of a target increases its spectral radiance and causes errors in radiometric temperature measurements. When the magnitude of the reflected radiation is comparable to or larger than that of the emitted radiance, errors in optical temperature measurements tend to be large. At target temperatures below about 100 to 150°C, reflected radiation is usually the dominant source of error in radiation thermometry (Nutter, 1985). Under certain circumstances, such as in a billet-reheating furnace, neglecting the effect of reflected radiation may simply make the optical measurements useless. (Hottel, 1986).

When reflected radiation is significant, the analysis becomes more complicated because the radiation detected by a pyrometer will include reflected and emitted components. Taking radiation emitted and reflected from the surface into consideration, pyrometer readings at wavelengths  $\lambda_1$  and  $\lambda_2$  are given by

$$\begin{aligned} R_{\lambda_1} &= \epsilon_{\lambda_1} E_{b\lambda_1}(T_{surf}) + (1 - \epsilon_{\lambda_1}) E_{b\lambda_1}(T_{surr}) \\ R_{\lambda_2} &= \epsilon_{\lambda_2} E_{b\lambda_2}(T_{surf}) + (1 - \epsilon_{\lambda_2}) E_{b\lambda_2}(T_{surr}) \end{aligned} \quad (6)$$

where  $T_{surf}$  and  $T_{surr}$  are the actual temperature of the surface and the effective temperature of the surroundings. Note that  $T_{surr}$  is a fictitious temperature which accounts for the temperatures of the sources of the reflected radiation and their geometric disposition.

5 Two wavelengths are necessary to give two equations in the two unknown temperatures,  $T_{surf}$  and  $T_{surr}$ . The emissivities in the system (6) are still undetermined by these relations and must be obtained from independent measurements. The readings  $R_{\lambda_i}$  have the same units as  $E_{\lambda_i}$ , and  $(1-\epsilon_{\lambda_i})$  is, the spectral reflectivity of the opaque surface. By Kirchhoff's law, the reflectivity and  
10 emissivity sum to one.

Obtaining the emissivity of solid materials is difficult since  $\epsilon_{\lambda}$  depends on angle, wavelength, and temperature of the surface. One approach to eliminating the need to know  $\epsilon_{\lambda_1}$  and  $\epsilon_{\lambda_2}$  involves taking readings at three wavelengths instead of two. The resulting three equations contain five unknowns:

$$\begin{aligned} 15 \quad R_{\lambda_1} &= \epsilon_{\lambda_1} E_{b\lambda_1}(T_{surf}) + (1 - \epsilon_{\lambda_1}) E_{b\lambda_1}(T_{surr}) \\ R_{\lambda_2} &= \epsilon_{\lambda_2} E_{b\lambda_2}(T_{surf}) + (1 - \epsilon_{\lambda_2}) E_{b\lambda_2}(T_{surr}) \\ R_{\lambda_3} &= \epsilon_{\lambda_3} E_{b\lambda_3}(T_{surf}) + (1 - \epsilon_{\lambda_3}) E_{b\lambda_3}(T_{surr}) \end{aligned} \quad (7)$$

where, again,  $T_{surf}$  and  $T_{surr}$  are the actual temperature of the surface and the  
20 effective temperature of the surroundings.

If the surface can be assumed gray at the wavelengths of interest, i.e.,  $\epsilon_{\lambda_1} = \epsilon_{\lambda_2} = \epsilon_{\lambda_3} = \epsilon$ , equations (7) can be solved since there are only three unknowns, namely  $T_{surf}$ ,  $T_{surr}$ , and  $\epsilon$ . The system is highly nonlinear and transcendental, and must be solved numerically. The assumption of identical spectral emissivities,  
25 although somewhat restrictive, is reasonable if the wavelengths and the applications are carefully selected. In many cases, the emissivity of a surface can be treated as a constant if the wavelengths at which the measurements are taken are within a narrow range. For example, the spectral, normal emissivity of heavily oxidized stainless steel at 1200 K is close to 0.8, over a wavelength range from 0.4  $\mu\text{m}$  to 2  
30  $\mu\text{m}$  (Incropera and DeWitt, 1985).

One potential application of pyrometric analysis is the sensing of temperatures of solids, particularly solids in closed containers, e.g., solids contained in heated kilns. For example, the temperature of the bed of solids in rotary kilns is

a key parameter in hazardous waste incineration. However, direct measurement of the bed temperature in full-scale rotary kilns is difficult due to the motion and structural configuration of the kiln as well as the harshness of the kiln environment.

Because of this, an indirect approach is frequently applied in which the temperature of the combustion gases at the exit of the kiln is measured and used to control operating conditions. It is then assumed that the temperature of the solids is maintained within normal limits if the proper combustion gas temperature range is maintained. This common practice is often not reliable. Significant discrepancies often exist between the temperature of the exit gas and the temperature of the solids.

One possible technique for the direct measurement of the temperature of the solids is infrared optical pyrometry. At first glance this appears to be a feasible technology if air purging can keep lenses clean and water cooling can prevent the electronics from overheating (Andreyuk, 1989). An optical method might not obtain the true bed temperature for several reasons. The wavelengths selected for optical measurements must avoid the principle absorption and emission bands of the major combustion gas species such as  $H_2O$  and  $CO_2$ . An infrared pyrometer measures the radiation intensity from a surface which is the sum of emitted and reflected components. If a relatively cool surface is placed in hot surroundings, then the reflected component of the intensity will cause the temperature to be overestimated. The sight path of the pyrometer might be obscured by small, suspended particles such as smoke, soot, and entrained fines, therefore, the optically determined temperatures will be affected by particle interference (e.g., emission, absorption and scattering) and consequently involve errors.

There exists a need for an optical technique which eliminates interferences from hotter surroundings.

The two-color technique of the instant invention gives rise to a system of two equations in four unknowns.

$$\begin{aligned} R_{\lambda_1} &= \varepsilon_{\lambda_1} E_{b\lambda_1}(T_{surf}) + (1 - \varepsilon_{\lambda_1}) E_{b\lambda_1}(T_{surr}) \\ R_{\lambda_2} &= \varepsilon_{\lambda_2} E_{b\lambda_2}(T_{surf}) + (1 - \varepsilon_{\lambda_2}) E_{b\lambda_2}(T_{surr}) \end{aligned}$$

These two equations can be solved if the spectral emissivities of the surface are known.

FIG. 1 illustrates that the radiation detected by an optical pyrometer will include emitted and reflected components. Here, the surfaces are assumed to be diffuse emitters and reflectors and the effects of participating gases are neglected.

To usefully apply equations (6), the proper choices for  $\lambda_1$  and  $\lambda_2$  must be made. If the optical measurement is conducted in the exit region of the kiln, where the interferences are not as severe as upstream, and, if the wavelength windows of the optical pyrometry are selected such that the emission and absorption bands of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  can be avoided, the major systematic errors involved in optical measurement for solid temperatures will then most likely result from reflected radiation. Factors affecting these choices include avoidance of the  $\text{CO}_2$  and  $\text{H}_2\text{O}$  emission and absorption bands, and the selection of wavelengths that can see through clouds of soot, dust, and smoke.

The principle emission and absorption bands for  $\text{CO}_2$  are 2.64-2.84, 4.13-4.5, and 13-17  $\mu\text{m}$ . For  $\text{H}_2\text{O}$ , the bands are 2.55-2.84, 5.7-7.6, and 12-25  $\mu\text{m}$  (Hottel and Sarofim, 1967).

The mean penetration distance before scattering is inversely proportional to the scattering cross section of the dust, soot, and smoke particles. Since the diameter of soot particles is small relative to the wavelengths typical of thermal radiation, the scattering cross section is proportional to  $\lambda^{-4}$  where  $\lambda$  is the wavelength (Siegel and Howell, 1981). Increasing the wavelength greatly increases the penetration distance before scattering. Hence, longer wavelengths are desirable for seeing through clouds of soot.

The final factor to consider in selecting wavelengths for equations (6) involves the sensitivity of  $T_{\text{surf}}$  and  $T_{\text{surf}}$  to errors in the readings,  $R_{\lambda_1}$  and  $R_{\lambda_2}$ . By taking readings at two wavelengths, equations (6) can be solved simultaneously to find both  $T_{\text{surf}}$  and  $T_{\text{surf}}$ . The design parameters are  $\lambda_1$  and  $\lambda_2$ . A preliminary sensitivity analysis to determine reasonable wavelengths is important. If  $T_{\text{surf}}$  and  $T_{\text{surf}}$ ,  $\lambda_1$  and  $\lambda_2$ , are specified, equations (6) can be used to calculate  $R_{\lambda_1}$  and  $R_{\lambda_2}$ . They can then be inverted to obtain  $T_{\text{surf}}$  and  $T_{\text{surf}}$  using a numerical solver for a nonlinear system. Finally, the inversion process can be repeated with perturbed

values of  $R\lambda_1$  and  $R\lambda_2$  to check on the sensitivity of the temperatures to errors in the readings. Errors of  $\pm 5$  percent were used in the example that follows.

The temperatures and wavelengths examined are summarized in Table 2.

The temperature of the surroundings was set at 1100 K and the temperature of the surface was set at 900 K. The Newton-Raphson method was used to solve for  $T_{\text{surf}}$  and  $T_{\text{surr}}$ . Two groups of calculations at wavelengths of 4-5 and 1-2  $\mu\text{m}$  were performed. These infrared wavelengths were chosen to avoid the principle bands of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ .

Table 2 Summary of sensitivity analysis

10 A. Longer wavelengths ( $\lambda_1 = 4 \mu\text{m}$ ,  $\lambda_2 = 5 \mu\text{m}$ ,  $\varepsilon = 0.9$ )

Test	$R_{\lambda_1}$ W/m <sup>2</sup> • $\mu\text{m}$	$R_{\lambda_2}$ W/m <sup>2</sup> • $\mu\text{m}$	Bed Temperature, K	Solid Temperature, K
$R_{\lambda_1} + 5\%$	7977	5534	836.1	1468
$R_{\lambda_1} - 5\%$	7217	5534	No roots found	No roots found
Standard	7597	5534	900	1100
15 $R_{\lambda_2} + 5\%$	7597	5811	812.3	1496
$R_{\lambda_2} - 5\%$	7597	5257	No roots found	No roots found

B. Shorter wavelengths ( $\lambda_1 = 1 \mu\text{m}$ ,  $\lambda_2 = 2 \mu\text{m}$ ,  $\varepsilon = 0.9$ )

Test	$R_{\lambda_1}$ W/m <sup>2</sup> • $\mu\text{m}$	$R_{\lambda_2}$ W/m <sup>2</sup> • $\mu\text{m}$	Bed Temperature, K	Solid Temperature, K
$R_{\lambda_1} + 5\%$	122.1	5242	878	1107
20 $R_{\lambda_1} - 5\%$	110.5	5242	902	1093
Standard	116.3	5242	900	1100
$R_{\lambda_2} + 5\%$	116.3	4980	889	1107
$R_{\lambda_2} - 5\%$	116.3	5504	911	1091

25 At  $\lambda_1 = 4 \mu\text{m}$  and  $\lambda_2 = 5 \mu\text{m}$ , the inversion process yielded two sets of roots, but the calculated temperatures were extremely sensitive to small errors in the readings  $R_{\lambda_1}$  and  $R_{\lambda_2}$ . For the other two cases at 4 and 5  $\mu\text{m}$  the perturbed readings were such that no roots were found. Going to shorter wavelengths of 1.0 and 2.0  $\mu\text{m}$  gave temperatures which were considerably less sensitive to errors in the pyrometer readings. For this reason, and because of the availability of instrumentation, 30 pyrometers reading at 1.05 and 2.2  $\mu\text{m}$  were chosen.

The two-color optical pyrometry technique was tested experimentally in three stages. 1) Verification tests were performed using a heavily oxidized copper plate.

The plate's emissivity was measured, as described below, and then the same plate was placed in a waterjacketed tray and inserted in a pilot-scale rotary kiln at elevated temperatures. This permitted the new technique to be tested under carefully controlled conditions. Copper was selected for verification purposes because of its high thermal conductivity. 2) Verification tests were also performed using sand and a clay-type soil in the pilot-scale kiln. The tests were conducted for both steady state and transient heating conditions. In conjunction with these tests, a new method was developed to obtain the required emissivities of the surfaces. 3) Interference studies were conducted to simulate the harsh conditions inside actual rotary kilns. These tests qualitatively examined the effects of smoke, soot, and entrained fines on optical pyrometry measurements.

The optical pyrometer is the key analytical instrument used in this example. Two single-color pyrometers were supplied by E<sup>2</sup>TECHNOLOGY Corporation: the PULSAR II, Model 7000SI (1.05  $\mu\text{m}$ ) and Model 7000FF (2.2  $\mu\text{m}$ ). These two pyrometers operate at wavelengths that avoid the principle emission and adsorption bands of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ .

To measure the emissivity of the copper plate, thermocouples were used with the two, single-color pyrometers and a 1.8 kW furnace. FIG. 2 shows a cross section of the furnace with the copper plate resting above the heating elements. The 1.8 kW furnace was used to heat a sample to 870°C (1600°F) at steady state in room-temperature surroundings. In order to eliminate the effects of reflection, the sample was heated electrically from below. The two thermocouples measured the thermal gradient inside the plate, from which the surface temperature of the oxidized copper was estimated by linear extrapolation. Knowing the temperature of the surface, T, the desired spectral emissivity was obtained by the procedure discussed above.

When silica sand or a clay-soil were placed in the same apparatus, their surfaces were highly nonisothermal, because of their low thermal conductivities, and the temperatures of their surfaces were difficult to measure. A new method for measurement of emissivities was developed using the apparatus shown in FIG. 3.

The device consists of an electrically heated sample of clay or sand which was heavily insulated on the sides and top. A thermocouple inserted at the insulation-sample interface was used to measure the initial surface temperature of



the sample after steady state conditions were reached. Then the insulating cover was suddenly removed after a pyrometer had been previously focused on the surface. The surface temperature was measured optically, with some delay, due to the response time ( $< 1$  second) of the instrument. Meanwhile, a pyrometer, 5 calibrated against a black body radiator, was sighted on the surface to get the brightness temperature  $T_B$ , from which  $E_\lambda$  was obtained through equation 4. According to equation 3, the ratio of  $E_\lambda/E_{b\lambda}$  gives  $\epsilon\lambda$ , which is the desired surface emissivity.

When sand and the clay-soil are placed in the same apparatus, their surfaces 10 are highly nonisothermal, because of their low thermal conductivities, and their surface temperatures are difficult to measure. A new method was developed using the apparatus shown in FIG. 3. The device consists of an electrically heated sample of clay or sand which is heavily insulated on the sides and top. A thermocouple inserted at the insulation-sample interface is used to measure the initial surface 15 temperature of the sample after steady state conditions have been reached. Then the upper layer of insulation is suddenly removed after a pyrometer has been sighted on the surface. The surface temperature can be read by the pyrometer after its 1 second response time. A data acquisition system was used to record the transient, optically determined brightness temperature,  $T_B$ . The initial surface brightness temperature, 20 used in determining sample emissivity, must then be obtained by extrapolating to time zero. More details are given below. A data acquisition system was used to record the transient optically determined brightness temperature,  $T_B$ . The initial brightness temperature of the surface used for determining emissivity of the sample must then be obtained by extrapolating to time zero.

25 A 130-kW, natural gas-fired, pilot-scale rotary kiln (Owens, 1991) and a water-cooled sample tray were employed to simulate the situation in which cool solid wastes are placed in a hot environment. A schematic of the tray is given in Fig. 4. The tray, with a thermocouple embedded in the sample of sand or clay, was kept at a relatively low temperature inside the kiln by the water-cooling system. 30 The cooled tray can be used for either the copper plate or for other materials with minor modifications. The rotary kiln and the associated afterburner are shown in FIG. 5. The variable swirl burner can produce temperatures of up to 1620°C in the 0.61-m-diameter and 0.61-m-long combustion chamber of the kiln. The burner and

-19-

main section were rotated at speeds up to 2.0 rpm; the exhaust section remained stationary. The kiln exhaust gas passed between two opposed, 49 kW natural-gas fired burners in an afterburner tower (Owens, 1991). FIG. 6 shows how two, single-color pyrometers were used to measure the spectral brightness temperatures of the sample surface inside the kiln.

For the interference studies, acetylene ( $C_2H_2$ ) was mixed with methane ( $CH_4$ ) and burned under fuel rich conditions to generate a sooty environment inside the kiln. The afterburner was operated under fuel-lean conditions to ensure a sufficiently safe overall fuel/air ratio. In addition, the clay soil, with a particle size of less than  $37 \mu m$ , was injected into the kiln through the burner to simulate the dusty environment typical of industrial rotary kilns. Commercial smoke emitters were used outside of the kiln to examine the interfering effects of smoke in the pyrometer sight path.

An OMEGA® WB-AAI interface card, installed in a Macintosh SE computer, with the associated software, was used to read and record the output from thermocouples and optical pyrometers. The applicable program is attached hereto as Appendix.

FIG. 7 gives the measured spectral emissivities of oxidized copper plate as a function of temperature, by the method described above. The difference in the two thermocouple readings in the plate was typically less than  $1^\circ C$  (the top one always read lower as expected). The small temperature gradient implied that the plate was close to isothermal condition and that the temperature of the surface could be estimated accurately.

To validate the two-color technique using the copper plate and the water cooled tray, two single-color pyrometers were used to measure the spectral brightness temperatures of the copper plate inside the kiln, as shown in FIG. 6. The resulting brightness temperatures were used to calculate the  $E_\lambda$ 's from equation (3). The  $E_{\lambda_i}$ , expressed as  $R_{\lambda_i}$ , and the corresponding emissivities shown in FIG. 7, were substituted in equations (6) and numerical solutions for the temperature of the surface and the effective temperature of the surroundings were obtained. The temperature of the plate was also measured by two thermocouples embedded in the copper as shown in FIG. 4. A suction pyrometer was employed to monitor the temperature of the gas in the center of the kiln cavity. The wall temperature of the

-20-

kiln was also continuously recorded during the experiment by a thermocouple inserted through the shell of the kiln to within 2 mm of the inner surface.

FIG. 8 shows the measured temperatures for the kiln and the water cooled copper plate inside the kiln. The test lasted for 60-70 minutes and the temperatures fell by roughly 110°C during the experiment which permitted the optical response to temperature variations to be examined. The results are encouraging and show good agreement between the optically and directly determined surface temperatures. In addition, the optically determined temperature of the surroundings and the gas temperatures obtained by the suction pyrometer are in good agreement.

FIGS. 9 and 10 show the measured emissivities of the sand and the clay soil. The data are consistent and reproducible. These results were obtained with the 1.8 kW furnace. The published spectral emissivity data (Touloukian, 1970) for pure crystalline SiO<sub>2</sub> at 1023°K are 0.4 and 0.063 at 1.0 μm and 2.0 μm. The discrepancies between the measured and literature values can be explained by the impurities present in the sand. No published spectral emissivity data for clay-soils have been found.

FIG. 11 shows additional results for sand placed in the water-cooled tray in the pilot-scale kiln. The temperature of the steel tray was measured by a thermocouple soldered to its surface. The temperature of the sand was measured by another thermocouple located 1.5 mm below its surface so that the optically determined temperature of the surface was somewhat higher than the value measured with the thermocouple. The optically determined temperature of the surroundings is between those of the suction pyrometer and the wall. The optically determined temperatures of the sand are quite scattered. A later section will show that this might be due to the sensitivity of the optically determined temperatures to errors in measured emissivities and pyrometer readings, especially when the emissivities are low as they are for sand.

Additional tests were performed with sand by suddenly loading 7.5 kg into the kiln. The rotation rate of the kiln was 2 rpm to ensure that the bed was in a continuous rolling motion and was nearly isothermal. A thermocouple was inserted in the sand to monitor its temperature. FIG. 12 shows a comparison of the optically measured temperatures of the sand with other temperature in the kiln. The

temperature of the sand as measured by the immersed thermocouple and by the optical technique are considerably different.

#### Emissivity Measurements

5 The accurate measurement of the emissivity of the surface is a key factor determining the success of the two-color technique. There are some difficulties involved in the measurement of emissivity. A conventional radiation ratio thermometer might help overcome these difficulties. It could be substituted for the thermocouples used in the tray-furnace studies to get the true temperature of the sample's surface, provided that the surface is gray.

10 However, the error in the temperature of the surface is not expected to be significant if a material with a high thermal conductivity is used. Hence, an oxidized Cu plate was used for the verification of this novel optical technique. Unfortunately, the contaminated solids encountered in thermal treatment applications generally have low thermal conductivities.

15 FIG. 3 shows the apparatus used for the instant method of determining emissivity. The instant technique involves suddenly exposing uniformly heated sand or clay to room temperature surroundings by removing a layer of insulation. The temperature of the rapidly cooling surface is recorded with a single-color pyrometer and the initial temperature is obtained by extrapolation of the cooling profile to time  
20 zero. FIG. 13 shows an example of this extrapolation scheme for the silica sand. Since the ratio of the thermal conductivities between sand and insulation materials can range from 5 to 10, the thermal gradients within the sand are less important. As a result, readings from a centrally located thermocouple at the sand-insulation interface can be approximated as the initial surface temperature,  $T$ , before the cover  
25 is removed. This surface  $T$  at time zero can be used to calculate  $E_{\lambda}$  by equation (1). Immediately after the sample is uncovered, the 1.05 and 2.2  $\mu\text{m}$  pyrometers monitor the dropping spectral, surface brightness temperatures as shown in the FIG. 13. The initial, spectral, brightness temperatures were determined by extrapolating these two curves to time zero. Once the three temperatures indicated by arrows in  
30 FIG. 13 were specified, the spectral emissivities of the sand could be calculated in the same way as for the copper plate described previously.

In performing this sudden exposure technique, special attention must be given to the following items: a) It takes several hours for the sand to reach a steady

state temperature; b) The pyrometer should be focused on the sample's surface before the insulation is put in place; c) The output of the thermocouples and of the pyrometers should be connected to the same data acquisition system to reduce systematic errors.

5           The analysis of both the water-cooled sand test, shown in FIG. 11, and the continuously rolling sand test, shown in FIG. 12, used the emissivities that were measured using the sudden exposure technique. Note that the emissivity of the surface might change in the rolling bed tests due to the decreased density of the tumbling sand. This possible effect has been ignored here.

10           The results in FIG. 12 show that a large temperature difference exists between the surface and the bulk regions of the sand, the surface being much hotter. As time increases, this temperature difference decreases. This difference can be attributed to the rapid heating of the exposed bed surface by radiation from the surroundings during the brief surface exposure interval.

15           The software which was developed to solve equations 6 (see Appendix) was used to investigate the sensitivity of the optically determined temperatures to errors in the pyrometer readings or brightness temperatures. FIG. 14 shows typical results for a surface with an emissivity of 0.9. For errors in the brightness temperature of  $\pm 10$  °F, the errors in calculated kiln temperatures and solid temperature are  
20           tolerable for wavelengths of 1.05 and 2.2  $\mu\text{m}$ .

          FIG. 15 shows the same results for an emissivity of 0.3. This value roughly corresponds to the values measured for sand. For errors in the brightness temperature of  $\pm 10$  °F, the errors in the calculated kiln temperature are still acceptable. Unfortunately, the errors in the calculated solid temperature become  
25           significant. This observation may explain the discrepancies seen in the sand data shown earlier. These errors can be minimized by careful calibration and operation of the instrumentation in the laboratory environment. However, the sensitivity shown in FIG. 15 is such that it is doubtful that careful calibration will solve the problem. This is especially true in industrial applications where it will be more  
30           difficult to maintain optimum instrument performance.

          In addition to errors in pyrometer readings, the software was used to study the sensitivity of the new two color technique to errors in surface emissivity. FIGS. 16 and 17 illustrate the errors in the resolved kiln and solids temperatures due

errors of  $\pm 0.02$  in emissivities of 0.9 and 0.3, respectively. For an emissivity of 0.9, the calculated kiln temperatures are more sensitive to these errors, while the calculated solids' temperatures are more sensitive at lower emissivities. This can be explained as follows. From equations 6 and 7, it is clear that the readings,  $R_N$ , consist of two parts, one is a function of the solids surface temperature,  $T_{surf}$ , and the other of the surroundings temperature,  $T_{surr}$ . For the lower emissivity materials, reflection from the surroundings dominates the readings so that the intensity is more responsive to the surroundings' temperature and the optical system becomes a better monitor of the surroundings' temperature. On the other hand, a higher emissivity material makes the pyrometers more responsive to the solids' temperature.

#### Transient, Batch Experiments in the Pilot-Scale Rotary Kiln

The results in FIG. 12 show a large temperature difference between the surface and the bulk temperature of the sand bed, the surface being much hotter. As the time increases, this temperature difference decreases. This difference can be attributed to greater radiation flux from the kiln surroundings initially and/or to rapid heating of the exposed bed surface by radiation from the surroundings during the brief surface exposure interval.

A penetration model was used to estimate the surface temperature of the bed under these conditions. Radiative transfer is the only heat transfer mode considered because it dominates at the high temperatures examined. The heat flux to the surface,  $q_0''$ , which is assumed constant over the brief exposure interval of less than 2 seconds, is given by

$$q_0'' = \varepsilon \sigma (T_w^4 - T_i^4) \quad (8)$$

where  $\varepsilon$  is the total emissivity of the surface,  $\sigma$  is the Stefan-Boltzmann constant, and  $T_w$  and  $T_i$  are temperatures of the kiln wall and of the surface of the sand at time zero. The corresponding temperature of a semi-infinite solid, as a function of time and distance from the surface, is given by Incropera and Dewitt (1985)

$$T(x, t) - T_i = \frac{2q_0''(\alpha t / \pi)^{1/2}}{k} \exp\left(\frac{x}{4\alpha t}\right) - \frac{q_0''x}{k} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) \quad (9)$$

At  $x=0$ , equation (9) becomes

$$T(0,t) - T_i = \frac{2q_0''(\alpha t / \pi)^{1/2}}{k} \quad (10)$$

where  $\alpha = k/\rho c$ .

5 A sample calculation for sand at  $T_w=870^\circ\text{C}$  and  $T_i=296^\circ\text{C}$  shows that the temperature of the surface rises to  $100^\circ\text{C}$  higher than bulk bed temperature in 2 seconds (See Appendix B) and to about  $70^\circ\text{C}$  higher in 1 second. Hence, at least part of the difference between the temperatures of the bulk and of the surface of the bed can be attributed to transient heating of the surface.

#### Interference from Smoke, Soot, and Dust

10 Most of the high temperature experimental work presented above focuses on the results from a natural gas-fired, pilot-scale rotary kiln. The gas phase was relatively free of particles of smoke, soot, and dust. In industrial-scale rotary kilns, pyrometry readings may be compromised by suspended particles. Preliminary experiments were performed to look at the sensitivity of the two-color technique to  
15 these interferences.

The smoke interference tests were conducted outside of the rotary kiln simulator using the 1.8 kW furnace with a heavily oxidized stainless steel plate and smoke emitters obtained from REGIN HVAC PRODUCTS, Inc. FIG. 18 gives results for the two single-color pyrometers at 1.05 and 2.2  $\mu\text{m}$ . The tests started  
20 with no smoke present, then three smoke emitters placed around the target were lit in sequence with approximately three minutes between ignitions. The two pyrometers were arranged so that both shared nearly the same sight path. The degree of interference varied widely as the smoke plume shifted in and out of the sight paths. However, from FIG. 18 it appears that the 2.2  $\mu\text{m}$  pyrometer was  
25 much less sensitive to the smoke than was the 1.05  $\mu\text{m}$  unit. This observation supports the conclusions based on scattering theory.

Incomplete combustion and poor mixing in industrial rotary kilns can cause a tremendous amount of soot to form. Optical pyrometer readings are sensitive to interferences from soot. An interference study was conducted by injecting acetylene  
30 and natural gas into the kiln at a stoichiometry of 0.7. Fuel lean conditions were maintained in the afterburner at all times. The tests were started after the water-cooled sample tray with the copper plate was placed in the kiln and the entire system was allowed to come to thermal equilibrium. In addition to optical

-25-

pyrometer readings at 1.05 and 2.2  $\mu\text{m}$ , thermocouples inserted in the copper yielded temperatures during the experiments.

A set of tests at acetylene flow rates of 9.2 (5.4), 14.1 (8.3), and 18.7 (11.0)  $\text{m}^3/\text{min}$  (CFH) were performed. The radiation intensities measured by the pyrometers increased with increasing flow rates. FIG. 19 shows the effects on the brightness temperatures and on the optically determined surface temperatures at an acetylene flow rate of 18.7  $\text{m}^3/\text{min}$  (11.0 CFH). Temperatures were also recorded without any acetylene supplied to the kiln. Introducing the acetylene caused a significant increase in the reading of the 1.05  $\mu\text{m}$  pyrometer reading but had little effect at 2.2  $\mu\text{m}$ . The higher sensitivity of the 1.05  $\mu\text{m}$  pyrometer to soot agrees with the previous findings for smoke. The optically determined temperatures of the surface, based on the measured spectral emissivities for oxidized copper obtained earlier (0.9 and 0.85 for 1.05 and 2.2  $\mu\text{m}$ ), decreased as the acetylene flow rates and soot levels increased, the maximum decrease was about 33°C (60°F). To explore the sensitivity of the measurements to surface emissivity, the optically determined temperature of the surface was recalculated with an emissivity of 0.8 at both wavelengths. As shown in FIG. 19, the effect of the change in emissivity is negligible. The optically determined surface temperature for a low emissivity material is expected to be much more sensitive to errors in the pyrometer readings and to changes in emissivity. Note that the presence of soot increases the brightness temperatures at both wavelengths but leads to a reduction in the optically determined temperature of the surface. This is counter-intuitive but not surprising since the effect of soot (it produces a luminous flame in the kiln) is interpreted by the two-color system as an increase in the temperature of the surroundings.

During the soot study, small amounts of soot deposited on the cool surfaces of the sample tray. It is not known if this has a significant impact on the emissivity of the copper oxide.

#### Interference from Entrained Fines

The entrainment of fine particles from the burden inside rotary kilns is a serious problem in hazardous waste incineration and in many other processes. The fine particles are transported by a number of different mechanisms including suspension, saltation, and wall pick-up, and can be carried out of the kiln in the gas



stream (Gag, 1991). These suspended particles can interfere with the sight paths of pyrometers and can affect their brightness temperature readings.

In pilot-scale rotary kiln tests, fine clay-soil ( $< 37 \mu\text{m}$  in diameter) was added to the air stream of the burner at three different rates, 14.6, 42.1, and 62.5 g/min. This increased the luminosity of the flame. The experimental set-up was similar to that for the soot experiments. Before the tests started, the sample tray was allowed to come to thermal equilibrium and the dust injection air was left on before and after dust addition so as not to change the temperatures in the kiln. The effects of the dust on pyrometer brightness temperatures increased with increasing feed rates. FIG. 20 shows temperatures at a feed rate of 62.5 g/min. The effects on the pyrometer readings are significant and the interference at  $1.05 \mu\text{m}$  is more severe than that at  $2.2 \mu\text{m}$ . The effects of these changes on the optically determined surface temperature are small. Using the previously measured emissivities (0.9 and 0.85 for  $1.05$  and  $2.2 \mu\text{m}$ ), the clay caused the optically determined surface temperatures to increase by only  $9^\circ\text{C}$  ( $16^\circ\text{F}$ ), however a significant discrepancy exists between the optical and thermocouple readings for the temperatures of the copper plate. The interpretation of these results is complicated because a thin layer of clay covered the plate's surface and this certainly changed its spectral emissivities. For this reason, a set of lower emissivities (0.55 and 0.50 for  $1.05$  and  $2.2 \mu\text{m}$ ) were used to simulate the effect of the dust layer. As shown in FIG. 20, using the lower emissivities gives better agreement with the true temperature of the surface but introduces a larger error due to the reflected radiation. Note that the variations in  $T_{\text{surf}}$  due to the changes in the brightness temperatures caused by the dust are in opposite directions if the lower emissivities are used.

### Three-Color Technique

As indicated above, equations (6) are unsolvable unless the emissivities of the surface are known. In some industrial applications, the materials whose surface temperatures are of concern have consistent and unchanging properties over fairly broad wavelength bands. Their surface emissivities can be determined by prior, independent measurements. As a consequence, the two-color method described above may be employed to obtain both the true surface temperature and the effective temperature of the surroundings. Examples of such surfaces include steel

and cement clinker. However, other processes such as hazardous solid waste incineration, where the correction of pyrometer readings for reflected radiation is also desired, must deal with unspecified materials whose physical properties (e. g., emissivities) are unknown and highly variable.

- 5 A pyrometer using three wavelengths may find its greatest usefulness where the emissivities, although unknown, are independent of wavelength over the range of interest.

10 If a pyrometer is sited on a small target area in a large enclosure, and if the target surface is a diffuse emitter and reflector, then the apparent emissive power of the surface is

$$E_{b\lambda}(T_{\lambda}) - \epsilon_{\lambda} E_{b\lambda}(T_s) + (1 - \epsilon_{\lambda}) E_{b\lambda}(T_{sur})$$

where  $T_{\lambda}$  is the apparent temperature of the surface at wavelength  $\lambda$ ,  $\epsilon_{\lambda}$  is the emissivity of the surface at wavelength  $\lambda$ ,  $T_s$  is the actual temperature of the surface,  $T_{sur}$  is the effective temperature of the surroundings, and  $E_{b\lambda}$  is the emissive power of a black body at wavelength  $\lambda$ . When  $T_s = T_{sur}$ , equation 1 gives  $T_s = T_{\lambda}$ .

- 15 The quantity,  $T_{\lambda} - T_s$ , defines a *temperature measurement error*.

Measurements at three wavelengths yield three equations in five unknowns:

$$E_{b\lambda_1}(T_{\lambda_1}) - \epsilon_{\lambda_1} E_{b\lambda_1}(T_s) + (1 - \epsilon_{\lambda_1}) E_{b\lambda_1}(T_{sur})$$

$$E_{b\lambda_2}(T_{\lambda_2}) - \epsilon_{\lambda_2} E_{b\lambda_2}(T_s) + (1 - \epsilon_{\lambda_2}) E_{b\lambda_2}(T_{sur})$$

$$E_{b\lambda_3}(T_{\lambda_3}) - \epsilon_{\lambda_3} E_{b\lambda_3}(T_s) + (1 - \epsilon_{\lambda_3}) E_{b\lambda_3}(T_{sur})$$

If we also assume that the surface is grey then

$$\epsilon_{\lambda_1} = \epsilon_{\lambda_2} = \epsilon_{\lambda_3} = \epsilon$$

- 20 and there are now three equations in three unknowns. Solving the three equations simultaneously gives the temperature of the surface,  $T_s$ , the emissivity of the surface,  $\epsilon$ , and the effective temperature of the surroundings,  $T_{sur}$ .

Measurements at two wavelengths give two equations in two unknowns provided that the emissivity of the gray surface is known from an independent

source. A two-color approach (at roughly 1 and 2  $\mu\text{m}$ ) was tested in our laboratory and was shown to work satisfactorily over a wide range of combustion conditions.

Sample calculations using the above three equations and selected values of wavelength, emissivity, and temperature are shown in Tables A and B. The  
 5 wavelengths were chosen with due consideration of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  absorption bands. Table A gives three sets of wavelengths, emissivities, and temperatures. Table B gives the corresponding apparent temperatures and measurement errors.

Table A. Three sets of arbitrarily selected conditions.

10	Run 1	
	$T_s$ (K)	1000
	$T_{\text{sur}}$ (K)	1300
15	$\varepsilon$	0.3
	Run 2	
	$T_s$ (K)	800
20	$T_{\text{sur}}$ (K)	1100
	$\varepsilon$	0.7
	Run 3	
	$T_s$ (K)	1200
	$T_{\text{sur}}$ (K)	1300
	$\varepsilon$	0.5

Table B. The apparent temperatures and temperature measurement errors at the conditions of Table A.

Run 1			
$\lambda$ ( $\mu\text{m}$ )	$E_{b\lambda}(T_\lambda)$ ( $\text{W}/\text{m}^2 \cdot \mu\text{m}$ )	Apparent Surface Temperature $T_\mu$ (K)	Temperature Measurement Error $T_\lambda - T_s$ (K)
0.6	3.281E+1	1275.5	275.5
1.05	5.5168E+3	1259.5	259.5
2.2	3.6552E+5	1234.9	234.9
Run 2			
0.7	5.1218E+0	1033.5	233.5
1.0	2.3785E+2	1008.5	208.5
2.1	6.6497E+3	947.9	147.9
Run 3			
0.8	7.356E+2	1261.8	61.8
1.3	1.5074E+4	1256.7	56.7
2.3	3.9718E+5	1253.1	53.1

The system of equations (6) can be extended to give three equations in three unknowns.

$$\begin{aligned}
 R_{\lambda_1} &= \epsilon E_{b\lambda_1}(T_{surf}) + (1 - \epsilon) E_{b\lambda_1}(T_{surr}) \\
 R_{\lambda_2} &= \epsilon E_{b\lambda_2}(T_{surf}) + (1 - \epsilon) E_{b\lambda_2}(T_{surr}) \\
 R_{\lambda_3} &= \epsilon E_{b\lambda_3}(T_{surf}) + (1 - \epsilon) E_{b\lambda_3}(T_{surr})
 \end{aligned} \tag{7'}$$

Note that in equations (7'), the previous system with three equations in five unknowns has been reduced to system where, assuming  $R_{\lambda_1}$ ,  $R_{\lambda_2}$  and  $R_{\lambda_3}$  are known, only three variables,  $\epsilon$ ,  $T_{surf}$  and  $T_{surr}$  are unknown. equations (7') are therefore numerically solvable provided that the emissivity of the surface is independent of wavelength. The approach embodied in equations (7') has the advantage that if the surface changes, an accurate determination of its temperature is still possible.

### Computer Simulation Results

Computer simulations of the three-color idea have been performed to gain insights into the feasibility of the approach. Again, the Newton-Raphson method was used to solve equation (7').

5        Selecting the wavelengths at which the measurements are performed is important. The following general rules were taken into consideration.

- 1)        The principle emission and absorption bands of CO<sub>2</sub> and H<sub>2</sub>O need to be avoided;
- 2)        The assumption of a constant emissivity is better if a narrow range of  
10        wavelengths is selected;
- 3)        The spectral intensities based on Plank law of the visible portions of thermal radiation decrease rapidly with decreasing wavelength;
- 4)        The system is more sensitive to experimental errors when longer wavelengths are chosen.

15        Rule (2) above requires that the three wavelengths are as close together as possible. Table 3 shows the sensitivity of the temperatures determined by solving equations (7') to the wavelengths selected.

Table 3 The effect of wavelength selection on the ability  
to accurately invert equations 7

20	Case No. 1:					
	Wavelength	Brightness Temperature	Variable	Correct Value	Initial Guess	Resulting Value
	1.6 $\mu\text{m}$	1415.5 K	T <sub>surf</sub>	1300 K	1200 K	1341.2 K
	2.2 $\mu\text{m}$	1409.7 K	T <sub>surr</sub>	1500 K	1600 K	1553.8 K
25	2.4 $\mu\text{m}$	1408.5 K	Emissivity	0.5	0.3	0.72
	Case No. 2:					
	Wavelength	Brightness Temperature	Variable	Correct Value	Initial Guess	Resulting Value
	0.8 $\mu\text{m}$	1434.6 K	T <sub>surf</sub>	1300 K	1200 K	1293.8 K
	1.6 $\mu\text{m}$	1415.5 K	T <sub>surr</sub>	1500 K	1600 K	1496.6 K
30	2.2 $\mu\text{m}$	1409.7 K	Emissivity	0.5	0.3	0.48

In this table, results for two sets of wavelengths are presented: 1.6, 2.2, 2.4  $\mu\text{m}$  and 0.8, 1.6, 2.2  $\mu\text{m}$ . The results of the inversion calculations show that the second set of wavelengths gives a more accurate solution for  $\epsilon$ , T<sub>surf</sub>, and T<sub>surr</sub>. All

-31-

of the errors in this calculation results from rounding the brightness temperatures to one decimal point. In making this comparison, the same set of initial estimates for  $\epsilon$ ,  $T_{\text{surf}}$ , and  $T_{\text{surr}}$  are used. The greater accuracy of the second set is not surprising since, in set No. 1, wavelengths 2.2 and 2.4  $\mu\text{m}$  are so close together that the resulting brightness temperatures, 1409.7 and 1408.5 K, are not sufficiently distinct from each other. Hence, Rule (2), which attempts to ensure that the emissivity will be constant, can introduce large inaccuracies when using equations (7') due to the highly nonlinear nature of the system.

Using the three wavelengths, 0.8, 1.6 and 2.2  $\mu\text{m}$ , Table 4 gives computer simulation results based on equations (7') for three different sets of temperatures and emissivities.

Table 4 The computer simulation results using the three-color technique

Brightness Temperature	Variable	Correct Value	Initial Guess	Resulting Value
Case A:				
1180.1 K	$T_{\text{surf}}$	1100 K	1400 K	1089.7 K
1174.9 K	$T_{\text{surr}}$	1200 K	1600 K	1197.5 K
1173.2 K	Emissivity	0.3	0.3	0.26
Case B:				
1451.5 K	$T_{\text{surf}}$	1200 K	1100 K	1200.2 K
1379.9 K	$T_{\text{surr}}$	1600 K	1700 K	1600.3 K
1357.1 K	Emissivity	0.7	0.5	0.70
Case C:				
1396.1 K	$T_{\text{surf}}$	1300 K	1400 K	1300.2 K
1384.2 K	$T_{\text{surr}}$	1450 K	1550 K	1450 K
1380.8 K	Emissivity	0.5	0.3	0.50

Note that, for each case, the three brightness temperatures are calculated from the radiosity (emissive and reflective) the pyrometers detect. Each brightness temperature is rounded off to the first decimal point. The above simulation results clearly demonstrate the potential of this novel three-color technique in measuring the correct temperature of surfaces with unspecified emissivities where reflection from hotter surroundings cannot be overlooked.

### Error Analysis

The above calculations assume that there are no errors in the pyrometer readings or their corresponding brightness temperatures, other than those introduced by rounding the brightness temperatures to one decimal place. As indicated above, the calculated temperatures are subject to errors in the pyrometry readings. The sensitivity of the optically determined temperatures and emissivities to errors in the brightness temperatures is now considered.

In the above discussion of the two-color system, comparisons between the values of the temperatures measured by thermocouple to the calculated temperatures based on pyrometer readings implied that the resulting temperatures were sensitive to experimental errors. In Table 3, the values of  $R_{\lambda_i}$  ( $i=1, 2$ , and  $3$ ) are assumed to be exact with no error other than that due to rounding. The results presented in Table 3 show that the solution to equations (7') is extremely sensitive to errors in the readings,  $R_{\lambda_i}$ .

In practice, some degree of experimental error in the optical pyrometer readings is inevitable. Given the sensitivity of the solution to these errors, frequent or even on-line calibration is desired. A more fundamental error analysis is now presented in order to gain insight into the sensitivity of the multi-color techniques to errors. The examples presented here are for a two-color system, merely for the purpose of illustrative convenience. Similar examples can be prepared for three-color systems with little difficulty except that they are difficult to present graphically.

Calculations were performed with the surface emissivities  $\epsilon_{\lambda_1}=0.3$  at  $\lambda_1=1.05 \mu\text{m}$  and  $\epsilon_{\lambda_2}=0.4$  at  $\lambda_2=2.2 \mu\text{m}$ . The true surface temperature ranged from 1200 to 1400 K while the effective temperature of the surroundings ranged from 1400 to 1600 K. FIG. 21 shows a contour chart of brightness temperatures at  $\lambda_1$  and  $\lambda_2$ . With any combination of  $T_{\text{surf}}$  and  $T_{\text{surr}}$ , a corresponding set of two brightness temperatures, can be found with this chart. For instance, at  $T_{\text{surf}}=1270 \text{ K}$  and  $T_{\text{surr}}=1440 \text{ K}$ , the brightness temperatures are,  $T_{B\lambda_1} \approx 1400 \text{ K}$  and  $T_{B\lambda_2} \approx 1375 \text{ K}$ . With the same chart in hand, one might conclude that this process of finding  $T_{B\lambda_1}$  and  $T_{B\lambda_2}$  can be inverted and, given a set of brightness temperatures, the true values of  $T_{\text{surf}}$  and  $T_{\text{surr}}$  could be obtained just by looking at FIG. 21.

Unfortunately, for most applications, things are more complicated than this. FIG. 22 gives a picture of typical inversion calculations and the problems associated with them. In order to illustrate those results effectively, two separate graphs are given with the temperatures,  $T_{\text{surf}}$  and  $T_{\text{surr}}$ , represented by shades of gray. The graphs show that all of the roots of the system, corresponding to the meaningful values of  $T_{\text{surf}}$  and  $T_{\text{surr}}$ , are found within a narrow band. If there are significant errors associated with  $T_{\text{B}\lambda 1}$  and  $T_{\text{B}\lambda 2}$ , the intersection of these two brightness temperatures may fall outside this band, and no roots will be found. FIG. 22 also provides insight into how the roots respond to errors or changes in the brightness temperatures. For this particular case, simultaneously positive or negative errors of approximately the same magnitude, hereafter referred to as Type A errors, may lead to small changes in  $T_{\text{surf}}$ . Likewise for  $T_{\text{surr}}$ , if simultaneously positive or negative errors in the brightness temperatures occur, with an approximate ratio of 2:1 for  $\Delta T_{\text{B}\lambda 2}$  to  $\Delta T_{\text{B}\lambda 1}$ , the change in  $T_{\text{surr}}$  is small. In contrast, considerable errors can occur in both temperatures, or no roots may be found at all, as a result of errors in  $T_{\text{B}\lambda 1}$  and  $T_{\text{B}\lambda 2}$  that are in different directions. Hereafter, errors of this type are referred to as Type B errors.

The stability of a three-color system can be treated similarly. The above discussion can be repeated with three, three-dimensional graphs, since three brightness temperatures and one desired variable, either  $T_{\text{surf}}$ ,  $T_{\text{surr}}$  or  $\varepsilon$ , are involved. This three-color system will be explored below and it will be shown that the diameter of the three-dimensional, roughly cylindrical region in which convergence can be obtained is small, i.e., the system is sensitive to errors. The orientation of the region is diagonal which indicates relative stability if Type A errors in the  $T_{\text{B}\lambda i}$  are involved. An analysis of the sensitivity of a multi-color system to errors is necessary in order to specify the precision required of the proposed instrument.

Bearing the previously explored concepts in mind, a number of FORTRAN programs were developed to solve equations (1) and/or (5). These programs were used to investigate the sensitivity of the optically determined temperatures and/or the surface emissivity to errors in pyrometer readings.



### Two-Color Technique

FIG. 14 shows typical results for a surface with an emissivity of 0.9, corresponding to the oxidized copper used in the tests described earlier. The emissivity is assumed independent of wavelength. For errors in a single brightness  
5 temperature of  $\pm 5.6^{\circ}\text{C}$  ( $\pm 10^{\circ}\text{F}$ ), the errors in the optically determined temperatures are within 2 percent for wavelengths of 1.05 and 2.2  $\mu\text{m}$ .

FIG. 15 shows similar results for an emissivity of 0.3. The emissivity is again assumed independent of wavelength. This value roughly corresponds to the values measured for sand. For errors in the brightness temperature of  $\pm 5.6^{\circ}\text{C}$   
10 ( $\pm 10^{\circ}\text{F}$ ), the errors in the optically determined temperature of the surroundings are still acceptable. Unfortunately, the errors in the temperature of the solid become significant. This observation may explain the discrepancies seen in the sand data shown earlier. These errors can be minimized by more frequent calibration of the instrumentation in the laboratory and by on-line calibration in the field.

15 The sensitivity analysis presented in Fig. 14 and 15 is for Type B errors. Errors of this type are expected here since two separate, single-color pyrometers were used.

In addition to errors in pyrometer readings, the software was used to study the sensitivity of the two-color technique to errors in the emissivity of the surface.  
20 FIGS. 16 and 17 illustrate the temperatures of the surroundings and of the surface due to errors of  $\pm 0.02$  in baseline emissivities of 0.9 and 0.3, at both wavelengths. For an emissivity of 0.9, the optically determined temperatures of the surroundings are more sensitive to these errors, while the temperatures of the solids are more sensitive at lower emissivities. This can be explained as follows. From equations  
25 (6), it is clear that the readings,  $R_{\lambda_2}$ , consist of two parts, one is a function of the temperature of the surface,  $T_{\text{surf}}$ , and the other of the temperature of the surroundings,  $T_{\text{surr}}$ . For the lower emissivity materials, reflection from the surroundings dominates the readings so that the intensity is more responsive to the temperature of the surroundings and the optical system becomes a better monitor of  
30 the surroundings. On the other hand, a higher emissivity material makes the pyrometers more responsive to the temperature of the solids. Test results discussed above support this explanation. The two-color system is highly sensitive to the errors in the emissivity.

### Three-Color Technique

To examine the sensitivity of the three-color approach to unavoidable random errors, equations (7') were solved numerically. FIGS. 23 to 25 show the calculated changes in  $T_{surf}$ ,  $T_{surr}$  and  $\varepsilon$ , corresponding to the small, Type B errors in a single brightness temperature or reading at wavelengths 0.8, 1.6, and 2.2  $\mu\text{m}$ . The errors in the brightness temperatures range from -6 to +8 K. Errors outside this narrow range resulted in no roots to the equations (7') being found. FIGS. 23 to 25 show that the three-color system is extremely sensitive to all of these errors such that it is doubtful that even careful calibration will make the system workable if a combination of three, separate, single-color pyrometers were used. This is especially true in industrial applications where it will be more difficult to maintain optimum instrument performance.

Additional calculations on how errors propagate in the three-color system were performed in order to provide guidance on reducing the sensitivity of the system to errors and to minimize the errors. The following discussion examines these issues and it also includes an examination of Type A errors.

equations (7') expresses the relationship between the independent variables,  $T_{surf}$ ,  $T_{surr}$  and  $\varepsilon$ , and the dependent variables  $R_{\lambda_i}$ . The equations are highly nonlinear and must be solved numerically. To examine the sensitivity of  $T_{surf}$ ,  $T_{surr}$  and  $\varepsilon$  to errors in the readings or brightness temperatures of the pyrometers, equations (7') were inverted and expressed as

$$\begin{aligned} T_{surf} &= T_{surf}(T_{B\lambda_1}, T_{B\lambda_2}, T_{B\lambda_3}) \\ T_{surr} &= T_{surr}(T_{B\lambda_1}, T_{B\lambda_2}, T_{B\lambda_3}) \\ \varepsilon &= \varepsilon(T_{B\lambda_1}, T_{B\lambda_2}, T_{B\lambda_3}) \end{aligned} \quad (11)$$

where the right hand sides are symbolic expressions for the inverse functions. The analytical expressions for these functions do not exist but they can be used to examine the sensitivity of the system as follows.

The total differentials of the system can be written as

$$\begin{aligned} dT_{surf} &= \frac{\partial T_{surf}}{\partial T_{B\lambda_1}} dT_{B\lambda_1} + \frac{\partial T_{surf}}{\partial T_{B\lambda_2}} dT_{B\lambda_2} + \frac{\partial T_{surf}}{\partial T_{B\lambda_3}} dT_{B\lambda_3}, \\ dT_{surr} &= \frac{\partial T_{surr}}{\partial T_{B\lambda_1}} dT_{B\lambda_1} + \frac{\partial T_{surr}}{\partial T_{B\lambda_2}} dT_{B\lambda_2} + \frac{\partial T_{surr}}{\partial T_{B\lambda_3}} dT_{B\lambda_3}, \\ d\varepsilon &= \frac{\partial \varepsilon}{\partial T_{B\lambda_1}} dT_{B\lambda_1} + \frac{\partial \varepsilon}{\partial T_{B\lambda_2}} dT_{B\lambda_2} + \frac{\partial \varepsilon}{\partial T_{B\lambda_3}} dT_{B\lambda_3}, \end{aligned} \quad (12)$$

Numerically, one can approximate the above total differentials and partial derivatives using finite difference methods. Taking  $T_{surf}$  as an example, one can set  $dT_{surf} = \Delta T_{surf}$  and,  $\partial T_{surf} / \partial T_{B\lambda i} = \Delta T_{surf} / \Delta T_{B\lambda i}$  (where  $T_{B\lambda 2}$  and  $T_{B\lambda 3}$  are held constant). Forward differencing was used here. Theoretically, the total resulting error in  $T_{surf}$ , namely  $\Delta T_{surf}$ , is the sum of three components. Each component is the product of a *coefficient of error propagation*,  $\partial T_{surf} / \partial T_{B\lambda i}$ , and an error in  $T_{B\lambda i}$ ,  $\Delta T_{B\lambda i}$ .

Note that the radiosities ( $10^5 \text{ W/m}^2$ ), the brightness or actual temperatures ( $10^4 \text{ K}$ ) and the surface emissivity ( $10^0$ ) are of very different magnitudes. For the convenience of this discussion, normalizing all of the variables was performed as follows. In any specific case, once the wavelengths are selected, a set of radiosities or their corresponding brightness temperatures were determined by equations (7') for any given  $T_{surf}$ ,  $T_{surf}^\circ$  and  $\varepsilon$ . For example, for the wavelengths 0.8, 1.6 and 2.2  $\mu\text{m}$ ,  $T_{surf}^\circ = 1300 \text{ K}$ ,  $T_{surf}^\circ = 1500 \text{ K}$ , and  $\varepsilon^\circ = 0.4$ ,  $R_{\lambda 1}^\circ = 4692.4 \text{ W/(m}^2 \cdot \mu\text{m)}$  or  $T_{B\lambda 1}^\circ = 1450.3 \text{ K}$ ,  $R_{\lambda 2}^\circ = 67569.0 \text{ W/(m}^2 \cdot \mu\text{m)}$  or  $T_{B\lambda 2}^\circ = 1434.1 \text{ K}$  and  $R_{\lambda 3}^\circ = 75443.0 \text{ W/(m}^2 \cdot \mu\text{m)}$  or  $T_{B\lambda 3}^\circ = 1429.0 \text{ K}$ . The symbol ( $^\circ$ ) here stands for the correct value of a variable. All of the aforementioned correct values will be used as the *characteristic values* of the corresponding variables in the following discussion and the normalized variables will hereafter be denoted by the symbol ( $^*$ ). For example, if  $T_{surf} = 1310 \text{ K}$ , then  $T_{surf}^* = T_{surf} / T_{surf}^\circ = (1310 \text{ K}) / (1300 \text{ K}) = 1.008$ ; and if  $T_{B\lambda 1} = 1448 \text{ K}$ , then  $T_{B\lambda 1}^* = T_{\lambda 1} / T_{B\lambda 1}^\circ = (1448 \text{ K}) / (1450.3 \text{ K}) = 0.9984$ . Hence, the normalized variables are all of order  $10^0$  and the new, normalized system become

$$\begin{aligned}
 dT_{surf}^* &= \frac{\partial T_{surf}^*}{\partial T_{B\lambda 1}^*} dT_{B\lambda 1}^* + \frac{\partial T_{surf}^*}{\partial T_{B\lambda 2}^*} dT_{B\lambda 2}^* + \frac{\partial T_{surf}^*}{\partial T_{B\lambda 3}^*} dT_{B\lambda 3}^* \\
 dT_{surf}^* &= \frac{\partial T_{surf}^*}{\partial T_{B\lambda 1}^*} dT_{B\lambda 1}^* + \frac{\partial T_{surf}^*}{\partial T_{B\lambda 2}^*} dT_{B\lambda 2}^* + \frac{\partial T_{surf}^*}{\partial T_{B\lambda 3}^*} dT_{B\lambda 3}^* \\
 d\varepsilon^* &= \frac{\partial \varepsilon^*}{\partial T_{B\lambda 1}^*} dT_{B\lambda 1}^* + \frac{\partial \varepsilon^*}{\partial T_{B\lambda 2}^*} dT_{B\lambda 2}^* + \frac{\partial \varepsilon^*}{\partial T_{B\lambda 3}^*} dT_{B\lambda 3}^*
 \end{aligned} \tag{13}$$

The normalized, partial derivatives appearing in equations (13) are plotted in FIGS. 26 to 28 as a function of the normalized brightness temperature. For example, FIG. 26 gives  $\partial T_{surf}^* / \partial T_{B\lambda i}^*$  as a function of  $T_{B\lambda i}^*$  which is  $(T_{B\lambda i} \pm j) / T_{B\lambda i}^\circ$ ,  $i=1, 2, 3$  and  $j=0, 1, \dots, 6$ . The error in the brightness temperatures, given by the

-37-

integer  $j$ , was varied over a limited range because large variations made it impossible to solve equations (7'), i.e., it was outside of the range over which the roots of the system exist. FIGS. 27 and 28 give similar plots for  $\partial T_{\text{sur}}^* / \partial T_{\lambda_i}^*$  and  $\partial \varepsilon^* / \partial T_{B\lambda_j}^*$ .

5            Significant insights can be gained from FIGS. 26 to 28. First, the partial derivatives are as large as +1000 and -1400. This means that small errors in the brightness temperature will be amplified dramatically into the total error estimated by equations (13). The severity of the total error depends on the relative location of the errors as given by the normalized brightness temperatures. Second, the figures  
10 show that the partial derivatives with respect to  $T_{B\lambda_2}^*$  are always negative while the other derivatives are always positive. As shown below, this can lead to cancellation of errors and improved stability. Third, the error, if it occurs in the single, shortest wavelength ( $0.8 \mu\text{m}$ ), will be relatively unimportant since its coefficients of error propagation are smaller than the others. Recall the above discussion, that longer  
15 wavelengths tend to increase the sensitivity of a system to errors and recall Rule 4 above. Finally, FIGS. 26-28 reveal the reason why errors of Type A are less detrimental. Recall that errors of Type A are all in the same direction and are of approximately the same magnitude. Errors of Type B are in different directions and include errors which affect only one brightness temperature, the other temperatures  
20 being correct. For errors of Type A, the individual errors tend to cancel each other with the result that there is a significantly smaller affect on the whole system. On the other hand, errors of Type B can lead to large total errors and instabilities.

The above discussion is critically important to the design of the instrumentation. If a three-color system is designed in a fashion similar to the two,  
25 single-color system tested in this study, with three individual units and their separate lens/sensor-amplifier display systems, errors of Type B will be unavoidable and the system will be extremely difficult, if not impossible, to use. However, if the instrument is designed and fabricated in such a way that only one lens/sensor-amplifier-display system is shared by all three wavelengths with selected  
30 spectral signals produced from a rotating filter wheel, the stability and sensitivity of the system will be much improved. This is because if the frequency at which the filter wheel completes a circle is sufficiently high compared to the fluctuation frequency of the system, it is reasonable to assume that few errors of Type B will

-38-

occur if the system is carefully calibrated. The effects of the magnitude of the error on the optically determined temperatures and emissivity, as they are most likely caused by the fluctuating zero shifts of the lens/sensor-amplifier-display system, can also be reduced. This can be accomplished if the time-averaged values of the  
 5 optically determined temperatures and emissivity are taken over the period (reciprocal of frequency) of the system's fluctuation.

Examples of the calculated insensitivity of the system to errors of Type A are shown in FIG. 29 where, as before, the baseline temperatures and emissivity are  $T_{\text{surf}}=1300$  K,  $T_{\text{surr}}=1500$  K and  $\varepsilon=0.4$  at wavelengths of 0.8, 1.6 and 2.2  $\mu\text{m}$ .  
 10 The errors are applied equally to all of the brightness temperatures. FIG. 29 shows that the resulting calculated values of  $T_{\text{surf}}$ ,  $T_{\text{surr}}$  and  $\varepsilon$  are relatively close to the baseline values. The computer simulation results show that the three-color system is fairly stable within a range of brightness temperature of  $\pm 80$  K. These results shows that the three-color technique is a feasible approach if the errors in the  
 15 individual brightness temperatures are all in the same direction and of similar magnitude.

In order to further reduce the introduction of errors into the analysis, the pyrometer signals at the individual wavelengths,  $R_{\lambda_i}$ , need not be converted to brightness temperatures,  $T_{B\lambda_i}$ . They can be retained as voltage or amperage signals  
 20 which are linearly and directly related to the radiosity. The advantages of doing this are shown as follows.

Plank law is, according to the theory,

$$E_{\lambda} = C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} \quad (1)$$

25 equation (1) is for nonblack surfaces since the temperature,  $T_B$ , is the brightness temperature. If the brightness temperature is also accounting for reflected radiation,  $E_{\lambda_i}$  is replaced with a reading,  $R_{\lambda_i}$ . The expression of  $T_{B\lambda_i}$  as a function of  $R_{\lambda_i}$  is given by

$$T_{B\lambda_i} = \frac{C_2}{\lambda_i \ln \left( \frac{C_1}{\lambda_i^5 R_{\lambda_i}} + 1 \right)} \quad (14)$$

Normalizing the  $T_{B\lambda_i}$  and  $R_{\lambda_i}$  using the  $T_{B\lambda_i}^\circ$  and  $R_{\lambda_i}^\circ$  given previously, equation (14) can be normalized as

$$T_{B\lambda_i}^* = \frac{C_2}{T_{B\lambda_i}^* \lambda_i \ln \left( \frac{C_1}{\lambda_i^5 R_{\lambda_i}^* R_{\lambda_i}^\circ} + 1 \right)} \quad (15)$$

5

Taking the derivative of  $T_{B\lambda_i}^*$  with the respect to  $R_{\lambda_i}^*$  gives

$$\frac{dT_{B\lambda_i}^*}{dR_{\lambda_i}^*} = \frac{C_1 C_2}{T_{B\lambda_i}^* \lambda_i^6 R_{\lambda_i}^* \left( \frac{C_1}{\lambda_i^5 R_{\lambda_i}^* R_{\lambda_i}^\circ} + 1 \right) \ln^2 \left( \frac{C_1}{\lambda_i^5 R_{\lambda_i}^* R_{\lambda_i}^\circ} + 1 \right)} \quad (16)$$

10 Since the term  $dT_{B\lambda_i}^*$  in equations (13) can be written as

$$dT_{B\lambda_i}^* = \frac{dT_{B\lambda_i}^*}{dR_{\lambda_i}^*} dR_{\lambda_i}^* \quad (17)$$

substituting for the  $dT_{B\lambda_i}^*$  with the above expression, equations (13) become

15

$$\begin{aligned} dT_{surf}^* &= \frac{\partial T_{surf}^*}{\partial R_{\lambda_1}^*} dR_{\lambda_1}^* + \frac{\partial T_{surf}^*}{\partial R_{\lambda_2}^*} dR_{\lambda_2}^* + \frac{\partial T_{surf}^*}{\partial R_{\lambda_3}^*} dR_{\lambda_3}^* \\ dT_{surr}^* &= \frac{\partial T_{surr}^*}{\partial R_{\lambda_1}^*} dR_{\lambda_1}^* + \frac{\partial T_{surr}^*}{\partial R_{\lambda_2}^*} dR_{\lambda_2}^* + \frac{\partial T_{surr}^*}{\partial R_{\lambda_3}^*} dR_{\lambda_3}^* \\ d\varepsilon^* &= \frac{\partial \varepsilon^*}{\partial R_{\lambda_1}^*} dR_{\lambda_1}^* + \frac{\partial \varepsilon^*}{\partial R_{\lambda_2}^*} dR_{\lambda_2}^* + \frac{\partial \varepsilon^*}{\partial R_{\lambda_3}^*} dR_{\lambda_3}^* \end{aligned} \quad (18)$$

20

FIG. 30 shows the relationship between the  $dT_{B\lambda_i}^*/dR_{\lambda_i}^*$  and the  $R_{\lambda_i}^*$  described by equation (16). The conditions for these calculations are the same as those associated with FIGS. 26 to 28. The small value of  $dT_{B\lambda_i}^*/dR_{\lambda_i}^*$  over a wide range of  $R_{\lambda_i}^*$  indicates that directly using  $R_{\lambda_i}$  as the independent variables, instead of the  $T_{B\lambda_i}$ , will reduce the sensitivity of the system to errors. The overall error can also be minimized since electronically converting  $R_{\lambda_i}$  to  $T_{B\lambda_i}$  and vice versa introduces additional errors. The numerical significance of the  $dT_{B\lambda_i}^*/dR_{\lambda_i}^*$  can also be determined quantitatively since the new *coefficients of error propagation*,  $\partial T_{surf}^*/\partial R_{\lambda_i}^*$ ,  $\partial T_{surr}^*/\partial R_{\lambda_i}^*$  and  $\partial \varepsilon^*/\partial R_{\lambda_i}^*$ , are the products of the old ones, namely  $\partial T_{surf}^*/\partial T_{B\lambda_i}^*$ ,  $\partial T_{surr}^*/\partial T_{B\lambda_i}^*$  and  $\partial \varepsilon^*/\partial T_{B\lambda_i}^*$ , shown in equations (13), and their corresponding  $dT_{B\lambda_i}^*/dR_{\lambda_i}^*$ . The data given in FIG. 30 indicate that, at 0.8 and 2.2  $\mu\text{m}$ , the new *coefficients of error propagation* will reduce to approximately

30

-40-

one-tenth and one-twentieth relative to the previous values. At  $1.6 \mu\text{m}$ , the new coefficient will be reduced about five-fold.

i) Using sand and heavily oxidized copper plate, the feasibility of using two, single color pyrometers to correct for the effects of reflected radiation when optically measuring the temperature of a relatively cool surface in hotter surroundings has been successfully demonstrated. This new technique requires that the emissivity of the surface be known.

ii) The surface temperature,  $T_{\text{surf}}$ , is sensitive to errors in the pyrometer readings, especially when the spectral surface emissivities are low. This sensitivity increases with increasing wavelength. The penetration depth before scattering increases with increasing wavelength. Hence, a compromise was reached and pyrometers operating at  $1.05 \mu\text{m}$  and  $2.2 \mu\text{m}$  were selected.

iii) A new technique has been developed to measure the spectral, surface emissivity for porous materials. This technique involves heating a sample of the material to a uniform temperature and then suddenly exposing it to cool surroundings. Knowing the initial temperature, and optically recording the brightness temperature, enables the calculation of the emissivity. This technique requires that the pyrometer reading be extrapolated back to time zero.

iv) Calculations performed with software developed as part of this project show that for materials with lower emissivities ( $< 0.4$ ), considerable errors in the surface temperatures can occur when applying the new two-color technique. Careful calibration and operation can help reduce these errors but their magnitude casts some doubt over the practical utility of this technology for low emissivity materials in industrial settings.

v) The results of a qualitative, interference study using smoke, soot, and dust imply that all of these materials can have significant effects on pyrometer readings. However, the interference study for soot and entrained fines has shown that these effects weakly affect the optically determined surface temperature for high emissivity materials. For materials with low surface emissivities, the effects of soot and smoke are expected to be much more severe and possibly even prevent converged solutions to equation 6 from being obtained. The experiments indicate that the  $2.2 \mu\text{m}$  pyrometer is less sensitive than the  $1.05 \mu\text{m}$  pyrometer to interferences from smoke, soot, and dust.

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- 42 -

Appendix A:  
The FORTRAN Computer Code

```

5      *23456789012345678901234567890123456789012345678901234567890123456789012
      *.....
      *.....          AUTHOR:  GEOFF SILCOX
      *.....          3290 MEB
      *.....          DEPARTMENT OF CHEMICAL ENGINEERING
10     *.....          UNIVERSITY OF UTAH
      *.....          SALT LAKE CITY, UTAH 84112
      *.....          PHONE:      (801) 581-8820
      *.....
      *.....          LAST UPDATED:      1 APRIL 1991
15     *.....
      *.....THIS PROGRAM ESTIMATES THE TEMPERATURES OF SURFACES BY TWO COLOR
      *.....PYROMETRY. TWO OPTIONS ARE AVAILABLE: IFLAG = 1 IMPLIES THAT
      *.....THE SOIL TEMPERATURE (TS) AND THE EFFECTIVE FURNACE TEMPERATURE
20     *.....(TF) ARE KNOWN AND WE WISH TO CALCULATED READING 1 (R1) AND
      *.....READING 2 (R2). IFLAG = 2 IMPLIES THAT R1 AND R2 ARE KNOWN AND
      *.....THAT WE WISH TO CALCULATE TS AND TF.
      *.....
      *.....REQUIRED INPUT
25     *.....
      *.....IFLAG: IF IFLAG = 1 THEN CALCULATE R1 AND R2.
      *.....          IF IFLAG = 2 THEN CALCULATE TS AND TF.
      *.....WL1 = WAVELENGTH 1, MICRONS.
      *.....WL2 = WAVELENGTH 2, MICRONS.
30     *.....EMIS = EMISSIVITY OF SOIL.
      *.....TS = TEMPERATURE OF SOIL OR INTIAL GUESS THEREOF, K.
      *.....TF = EFFECTIVE FURNACE TEMPERATURE OR INTIAL GUESS THEREOF, K.
      *.....R1 = READING 1 AT WAVELENGTH 1, W/M^2·MICRON.
      *.....R2 = READING 2 AT WAVELENGTH 2, W/M^2·MICRON.
35     *.....EPS = CONVERGENCE CRITERION FOR NEWTON RAPHSON METHOD, W/M^2.
      *.....IMAX = MAXIMUM ALLOWED NUMBER OF ITERATIONS.
      *.....DELTA = RELAXATION FACTOR.
      *.....THE UNITS ON C1 AND C2 ARE W·MICRONS^4/M^2 AND MICRONS-K,
      *.....RESPECTIVELY.
40     *.....
      *.....PROGRAM TWOCOL
      *.....OPEN(14,FILE='TC2.DAT',STATUS='OLD')
      *.....OPEN(18,FILE='TC2.RES',STATUS='NEW')
      *.....C1=3.742E8
      *.....C2=1.439E4
45     *.....READ(14,*) IFLAG,WL1,WL2,EMIS1,EMIS2
      *.....WRITE(18,11) IFLAG,WL1,WL2,EMIS1,EMIS2
11     *.....FORMAT(1X,4X/5X,'IFLAG = ',I2/5X,'WL1 = ',F12.4,' MICRONS'
      *.....C /5X,'WL2 = ',F12.4,' MICRONS'/5X,'EMIS1 = ',E14.5/5X,
50     *.....C 'EMIS2 = ',E14.5)
      *.....IF (IFLAG.EQ.1) THEN
      *.....    READ(14,*) *TS,TF
      *.....    WRITE(18,12) TS,TF
12     *.....FORMAT(1X,4X/5X,'TS = ',E14.5,' K'/5X,'TF = ',E14.5,' K')
      *.....R1 = RAD(EMIS1,TS,TF,WL1,C1,C2)
      *.....R2 = RAD(EMIS2,TS,TF,WL2,C1,C2)
      *.....WRITE(18,13) R1,R2
55     *.....FORMAT(1X,4X/5X,'R1 = ',E14.5,' W/M^2·MICRON'/5X,'R2 = ',
13     *.....C E14.5,' W/M^2·MICRON')

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- 43 -

```

      STOP
      ELSE IF (IFLAG.EQ.2) THEN
      READ(14,*) TS,TF,R1,R2,EPS,IMAX,DELTA
      WRITE(18,14) TS,TF,R1,R2,EPS,IMAX,DELTA
5      14      FORMAT(1X,4X/5X,'TS = ',E14.5,' K'/5X,'TF = ',E14.5,' K'
      C      /5X,'R1 = ',E14.5,' W/M^2-MICRON'/5X,'R2 = ',E14.5,
      C      ' W/M^2-MICRON'/5X,'EPS = ',E14.5,' W/M^2'
      C      /5X,'IMAX = ',I6/5X,'DELTA = ',F12.4)
      B1 = R1-RAD(EMIS1,TS,TF,WL1,C1,C2)
10      B2 = R2-RAD(EMIS2,TS,TF,WL2,C1,C2)
      DO 20 I=1,IMAX
      OTS = TS
      OTF = TF
      A11 = (1.-EMIS1)*DEDT(TF,WL1,C1,C2)
15      A12 = EMIS1*DEDT(TS,WL1,C1,C2)
      A21 = (1.-EMIS2)*DEDT(TF,WL2,C1,C2)
      A22 = EMIS2*DEDT(TS,WL2,C1,C2)
      DETJ = A11*A22-A21*A12
      IF (DETJ.EQ.0.) THEN
20      WRITE(18,23) I
      23      FORMAT(1X,4X,'JACOBIAN IS SINGULAR AND I = ',I4)
      STOP
      ENDIF
      DF = (B1*A22-B2*A12)/DETJ
25      DS = (B2*A11-B1*A21)/DETJ
      TF = OTF+DELTA*DF
      TS = OTS+DELTA*DS
      B1 = R1-RAD(EMIS1,TS,TF,WL1,C1,C2)
      B2 = R2-RAD(EMIS2,TS,TF,WL2,C1,C2)
30      TEST = SQRT(B1*B1+B2*B2)
      IF (TEST.LE.EPS) GO TO 99
      20      CONTINUE
      ELSE
      WRITE(18,21)
35      21      FORMAT(1X,4X,'INAPPROPRIATE VALUE OF IFLAG.')
      STOP
      ENDIF
      WRITE(18,15)
15      FORMAT(1X,4X,'IMAX EXCEEDED WITHOUT CONVERGENCE')
      STOP
40      99      CONTINUE
      WRITE(18,16) TF,TS,I
      16      FORMAT(1X,4X/5X,'TF = ',F12.4,' K'/5X,'TS = ',F12.4,' K'
      C      /5X,'I = ',I4)
45      STOP
      END
      *.....
      *.....
50      FUNCTION RAD(EMIS,TS,TF,WL,C1,C2)
      RAD = EMIS*EBL(TS,WL,C1,C2)
      RETURN
      END
      *.....
      *.....
55      FUNCTION EBL(T,WL,C1,C2)
      EBL = C1/(WL**5*(EXP(C2/(WL*T))-1.))
      RETURN
      END
      *.....

```

```
FUNCTION DEDT(T,WL,C1,C2)
DEDT = C1*C2*EXP(C2/(WL*T))/(WL**6*T*T*(EXP(C2/(WL*T))-1.))**2)
RETURN
END
```

5

\*.....

\*.....

\*2345678901234567890123456789012345678901234567890123456789012

Appendix B:  
Sample Calculation of Initial Surface Temperature

5 Assuming that radiation is the only heat transfer mode important here and that the bed can be approximated as a semi-infinite solid, the surface temperature of the bed can be described by:

$$T(0,t) - T_i - \Delta T - \frac{2q_0''(\alpha t/\pi)^{1/2}}{k}, \quad (B1)$$

where  $T(0,t)$  is the bed surface temperature at  $x=0$  at time  $t$ ,  $T_i$  is the initial bed temperature,  $q_0''$  is the radiative heat flux, and  $k$  and  $\alpha$  are thermal conductivity and thermal diffusivity, respectively.

Assuming  $q_0''$  is constant over a brief exposure time, it can be expressed as:

$$q_0'' = \epsilon \sigma (T_w^4 - T_i^4), \quad (B2)$$

where  $T_w$  is the kiln wall temperature,  $\epsilon$  is the total emissivity of the bed, and  $\sigma$  is Stefan-Boltzmann constant.

15 Taking  $T_w = 1460^\circ\text{F}$ ,  $T_i = 600^\circ\text{F}$  and the published physical properties data for sand at  $300^\circ\text{K}$  ( $\rho = 1515 \text{ kg/m}^3$ ,  $k = 0.27 \text{ W/m}\cdot\text{K}$ ,  $C_p = 800 \text{ J/kg}\cdot\text{K}$ ), one can easily calculate that  $q_0''$  is about  $60 \text{ kW/m}^2$ ,  $\Delta T = 118.4^\circ\text{K}$  ( $t = 1 \text{ sec}$ ), and  $\Delta T = 167.4^\circ\text{F}$  ( $t = 2 \text{ sec}$ ).

20 The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claim are to be embraced within their scope.

-46-

## APPENDIX C

## TWO-COLOR SIMULATION FORTRAN CODE

The following is a listing of computer code for the two-color pyrometry simulation. Samples of input and output files are also given.

## (1) Source code of "TWOCOL.FOR"

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C   THIS PROGRAM ESTIMATES THE TEMPERATURES OF SURFACES AND SURROUNDINGS
C   BY TWO COLOR PYROMETRY. TWO OPTIONS ARE AVAILABLE:
C
C   IFLAG = 1 IMPLIES THAT
C   THE SURFACE TEMPERATURE (TS) AND THE EFFECTIVE SURROUNDING TEMPERATURE
C   (TF) ARE KNOWN. READING 1 (R1) AND READING 2 (R2) AND THE CORRESPONDING
C   BRIGHTNESS TEMPERATURES (BRT1) AND (BRT2) ARE CALCULATED.
C
C   IFLAG = 2 IMPLIES THAT
C   R1 AND R2 (OR, BRT1 AND BRT2) ARE KNOWN. THE TS AND TF ARE
C   CALCULATED.
C
C   WRITTEN INITIALLY BY GEOFF SILCOX AND REVISED BY DACHUN GAO
C   TO INCLUDE BRIGHTNESS TEMPERATURE CALCULATION AND THE
C   SEQUENTIAL SCREEN TEST FOR SYSTEM SENSITIVITY TO ERRORS.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
*2345678901234567890123456789012345678901234567890123456789012
*
*.....REQUIRED INPUT
*.....
*.....IFLAG: IF IFLAG = 1 THEN CALCULATE R1, R2, BRT1, AND BRT2.
*.....      IF IFLAG = 2 THEN CALCULATE TS AND TF.
*.....WL1 = WAVELENGTH 1, MICRONS.
*.....WL2 = WAVELENGTH 2, MICRONS.
*.....EMIS1 = EMISSIVITY OF SURFACE AT WL1.
*.....EMIS2 = EMISSIVITY OF SURFACE AT WL2.
*.....TS = TEMPERATURE OF SURFACE, K.
*.....TF = EFFECTIVE SURROUNDING TEMPERATURE, K.
*.....R1 = READING 1 AT WAVELENGTH 1, W/M^2.MICRON.
*.....R2 = READING 2 AT WAVELENGTH 2, W/M^2.MICRON.
*.....BRT1 = BRIGHTNESS TEMPERATURE FOR R1, K.
*.....BRT2 = BRIGHTNESS TEMPERATURE FOR R2, K.
*.....ERR = ERROR RESULTING FROM OTHER SOURCES IN TERM OF BRIGHTNESS TEMPERATURE, K.
*.....EPS = CONVERGENCE CRITERION FOR NEWTON RAPHSON METHOD, W/M^2.
*.....IMAX = MAXIMUM ALLOWED NUMBER OF ITERATIONS.
*.....DELTA = RELAXATION FACTOR.
*.....
*.....THE UNITS ON C1 AND C2 ARE W.MICRONS^4/M^2 AND MICRONS.K, RESPECTIVELY.

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- 47 -

226

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*2345678901234567890123456789012345678901234567890123456789012
PROGRAM TWOCOL
DIMENSION ERR(101),EMISS1(101),EMISS2(101),BRT1(101),BRT2(101)
OPEN(14,FILE='TC11.DAT',STATUS='OLD')
OPEN(18,FILE='TC11.RES',STATUS='NEW')
C1=3.742E8
C2=1.439E4
      READ(14,*) N,IFLAG,WL1,WL2
      WRITE(*,11) N,IFLAG,WL1,WL2
      WRITE(18,11) N,IFLAG,WL1,WL2
11  FORMAT(1X,4X/5X,'N = ',I2/5X,'IFLAG = ',I2/5X,'WL1 = ',F12.4,
C    ' MICRONS'/5X,'WL2 = ',F12.4,' MICRONS')
      IF (IFLAG.EQ.1) THEN
        READ(14,*) EMIS1,EMIS2,TS,TF
        WRITE(18,12) EMIS1,EMIS2,TS,TF
        WRITE(*,12) EMIS1,EMIS2,TS,TF
12  FORMAT(1X,4X/5X,'EMIS1 = ',F14.2/5X,'EMIS2 = ',F14.2
C    /5X,'TS = ',F14.1,' K'/5X,'TF = ',F14.1,' K')
        R1 = RAD(EMIS1,TS,TF,WL1,C1,C2)
        R2 = RAD(EMIS2,TS,TF,WL2,C1,C2)
        WRITE(18,13) R1,R2
        WRITE(*,13) R1,R2
13  FORMAT(1X,4X/5X,'R1 = ',E14.5,' W/M^2·MICRON'/5X,'R2 = ',
C    E14.5,' W/M^2·MICRON')
        BRT11 = BRT(R1,WL1,C1,C2)
        BRT12 = BRT(R2,WL2,C1,C2)
        WRITE(18,17) BRT11,BRT12
        WRITE(*,17) BRT11,BRT12
17  FORMAT(1X,4X/5X,'BRT1 = ',F14.1,' K'/5X,'BRT2 = ',
C    F14.1,' K')
        GO TO 155
      ELSE IF (IFLAG.EQ.2) THEN
        READ(14,*) DUMMY,TS0,TF0,EPS,IMAX,DELTA
        WRITE(18,14) TS0,TF0,EPS,IMAX,DELTA
        WRITE(*,14) TS0,TF0,EPS,IMAX,DELTA
14  FORMAT(1X,4X/5X,'TS0 = ',F14.1,' K'/5X,
C    'TF0 = ',F14.1,' K'/5X,'EPS = ',E14.5,' W/M^2'
C    /5X,'IMAX = ',I6/5X,'DELTA = ',F12.4)
        DO 111 L=1,N
          READ(14,*) ERR(L),EMISS1(L),EMISS2(L),BRT1(L),BRT2(L)
111  CONTINUE
          WRITE(18,16)
          WRITE(*,16)
16  FORMAT(4X,'ERR',6X,'BRT1',6X,'BRT2',6X,'EMIS1',6X,
C    'EMIS2',6X,'TS',6X,'TF',10X,'I')
          DO 500 K=1,N
            EMIS1=EMISS1(K)
            EMIS2=EMISS2(K)
            TS=TS0
            TF=TF0
            R1 = EBL(BRT1(K),WL1,C1,C2)
            R2 = EBL(BRT2(K),WL2,C1,C2)
            B1 = R1-RAD(EMIS1,TS,TF,WL1,C1,C2)
            B2 = R2-RAD(EMIS2,TS,TF,WL2,C1,C2)
            DO 20 I=1,IMAX
              OTS = TS
              OTF = TF
              A11 = (1.-EMIS1)*DEDT(TF,WL1,C1,C2)
              A12 = EMIS1*DEDT(TS,WL1,C1,C2)
              A21 = (1.-EMIS2)*DEDT(TF,WL2,C1,C2)
              A22 = EMIS2*DEDT(TS,WL2,C1,C2)
              DETJ = A11*A22-A21*A12
              IF (DETJ.EQ.0.) THEN
                WRITE(18,23) K,I

```

-48-

```

                WRITE(*,23) K,I
23      FORMAT (1X,4X,'JACOBIAN IS SINGULAR AND ( K,I ) =
C        (',I4,',',I4,')')
                GO TO 100
                ENDIF
                DF = (B1*A22-B2*A12)/DETJ
                DS = (B2*A11-B1*A21)/DETJ
                TF = OTF+DELTA*DF
                TS = OTS+DELTA*DS
                B1 = R1-RAD(EMIS1,TS,TF,WL1,C1,C2)
                B2 = R2-RAD(EMIS2,TS,TF,WL2,C1,C2)
                TEST = SQRT(B1*B1+B2*B2)
                IF (TEST.LE.EPS) GO TO 99
20      CONTINUE
        ELSE
                WRITE(*,21)
                WRITE(18,21)
21      FORMAT(1X,4X,'INAPPROPRIATE VALUE OF IFLAG.')
                GO TO 100
        ENDIF
                WRITE(18,15) K,I
                WRITE(*,15) K,I
15      FORMAT(1X,4X,'IMAX EXCEEDED WITHOUT CONVERGENCE AND
C (K,I) = (',I4,',',I4,')')
                GO TO 100
99      CONTINUE
                WRITE(*,19) ERR(K),BRT1(K),BRT2(K),EMIS1,EMIS2,TS,TF,I
                WRITE(18,19) ERR(K),BRT1(K),BRT2(K),EMIS1,EMIS2,TS,TF,I
19      FORMAT(1X,F8.2,2X,F8.1,2X,F8.1,2X,F6.4,2X,F6.4,2X,F8.1,
C        2X,F8.1,2X,I6)
100     CONTINUE
500     CONTINUE
155     CONTINUE
        CLOSE(18)
        PAUSE
        STOP
        END
*2345678901234567890123456789012345678901234567890123456789012
*.....
*.....
        FUNCTION RAD(EMIS,TS,TF,WL,C1,C2)
        RAD = (1.-EMIS)*EBL(TF,WL,C1,C2)+EMIS*EBL(TS,WL,C1,C2)
        RETURN
        END
*.....
        FUNCTION EBL(T,WL,C1,C2)
        EBL = C1/(WL**5*(EXP(C2/(WL*T))-1.))
        RETURN
        END
*.....
        FUNCTION BRT(R,WL,C1,C2)
        BRT = C2/(WL*ALOG((C1/(R*WL**5)+1.)))
        RETURN
        END
*.....
        FUNCTION DEDT(T,WL,C1,C2)
        DEDT = C1*C2*EXP(C2/(WL*T))/(WL**6*T*(EXP(C2/(WL*T))-1.))**2)
        RETURN
        END
*.....
*.....
*2345678901234567890123456789012345678901234567890123456789012

```

-49-

## (2) A sample input file:

```

11
2
1.05
2.2
0.4
0.4
1200.
1600.
1.D-1
1000
1.D-1
-15.00 0.50 0.50 1426.00 1394.70
-12.00 0.50 0.50 1426.00 1397.70
-9.00 0.50 0.50 1426.00 1400.70
-6.00 0.50 0.50 1426.00 1403.70
-3.00 0.50 0.50 1426.00 1406.70
0.00 0.50 0.50 1426.00 1409.70
3.00 0.50 0.50 1426.00 1412.70
6.00 0.50 0.50 1426.00 1415.70
9.00 0.50 0.50 1426.00 1418.70
12.00 0.50 0.50 1426.00 1421.70
15.00 0.50 0.50 1426.00 1424.70

```

## (3) A sample output file:

```

N = 11
IFLAG = 2
WL1 = 1.0500 MICRONS
WL2 = 2.2000 MICRONS

TS0 = 1200.0 K
TF0 = 1600.0 K
EPS = 0.10000E+00 W/M^2
IMAX = 1000
DELTA = .1000

```

ERR	BRT1	BRT2	EMIS1	EMIS2	TS	TF	I
-15.00	1426.0	1394.7	.5000	.5000	1230.9	1517.2	113
-12.00	1426.0	1397.7	.5000	.5000	1244.2	1514.6	114
-9.00	1426.0	1400.7	.5000	.5000	1257.7	1511.6	114
-6.00	1426.0	1403.7	.5000	.5000	1271.5	1508.3	114
-3.00	1426.0	1406.7	.5000	.5000	1285.5	1504.4	114
.00	1426.0	1409.7	.5000	.5000	1300.0	1499.9	112
3.00	1426.0	1412.7	.5000	.5000	1315.1	1494.7	112
6.00	1426.0	1415.7	.5000	.5000	1331.2	1488.3	113
9.00	1426.0	1418.7	.5000	.5000	1348.8	1480.4	111
12.00	1426.0	1421.7	.5000	.5000	1369.1	1469.5	110
15.00	1426.0	1424.7	.5000	.5000	1396.5	1451.5	114



## APPENDIX D

## THREE-COLOR SIMULATION FORTRAN CODE

The following is a listing of the computer code for the three-color pyrometry simulation. Samples of input and output files are also given.

(1) Source code of "TRICOL.FOR"

```
C
C THIS PROGRAM ESTIMATES THE TEMPERATURES OF SURFACES AND SURROUNDINGS
C BY THREE COLOR PYROMETRY. TWO OPTIONS ARE AVAILABLE:
C
C IFLAG = 1 IMPLIES THAT
C THE SURFACE TEMPERATURE (TS), THE EFFECTIVE SURROUNDING TEMPERATURE
C (TF), AND THE EMISSIVITY ARE KNOWN. READING 1 (R1), READING 2 (R2),
C AND READING 3 (R3) AND THE CORRESPONDING BRIGHTNESS
C TEMPERATURES (BRT1), (BRT2), AND (BRT3) ARE CALCULATED.
C
C IFLAG = 2 IMPLIES THAT
C R1, R2, AND R3 (OR, BRT1, BRT2, AND BRT3) ARE KNOWN. THE TS, TF, AND
C THE EMISSIVITY ARE CALCULATED.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
*2345678901234567890123456789012345678901234567890123456789012
*
*.....REQUIRED INPUT
*.....
*.....IFLAG: IF IFLAG = 1 THEN CALCULATE R1 AND R2.
*.....      IF IFLAG = 2 THEN CALCULATE TS AND TF.
*.....WL1 = WAVELENGTH 1, MICRONS.
*.....WL2 = WAVELENGTH 2, MICRONS.
*.....WL3 = WAVELENGTH 3, MICRONS.
*.....EMIS = EMISSIVITY OF SURFACE AT WL1, WL2, AND WL3.
*.....TS = TEMPERATURE OF SURFACE, K.
*.....TF = EFFECTIVE SURROUNDING TEMPERATURE, K.
*.....R1 = READING 1 AT WAVELENGTH 1, W/M^2-MICRON.
*.....R2 = READING 2 AT WAVELENGTH 2, W/M^2-MICRON.
*.....R3 = READING 3 AT WAVELENGTH 3, W/M^2-MICRON.
*.....BRT1 = BRIGHTNESS TEMPERATURE FOR R1, K.
*.....BRT2 = BRIGHTNESS TEMPERATURE FOR R2, K.
*.....BRT3 = BRIGHTNESS TEMPERATURE FOR R3, K.
*.....ERR = ERROR RESULTING FROM OTHER SOURCES IN TERM OF BRIGHTNESS TEMPERATURE, K.
*.....EPS = CONVERGENCE CRITERION FOR NEWTON RAPHSOON METHOD, W/M^2.
*.....IMAX = MAXIMUM ALLOWED NUMBER OF ITERATIONS.
*.....DELTA = RELAXATION FACTOR.
*.....
*.....THE UNITS ON C1 AND C2 ARE W-MICRONS^4/M^2 AND MICRONS-K, RESPECTIVELY.
*2345678901234567890123456789012345678901234567890123456789012
```

- 51 -

```

PROGRAM TRICOL
DIMENSION ERR(101),BRT1(101),BRT2(101),BRT3(101)
OPEN(14,FILE='TC8.DAT',STATUS='OLD')
OPEN(18,FILE='TC8.RES',STATUS='NEW')
  C1=3.742E8
  C2=1.439E4
  READ(14,*) N,IFLAG,WL1,WL2,WL3
  WRITE(18,11) N,IFLAG,WL1,WL2,WL3
11  FORMAT(1X,4X/5X,'N = ',I2/5X,'IFLAG = ',I2/5X,'WL1 = ',F12.4,
C    ' MICRONS'/5X,'WL2 = ',F12.4,' MICRONS'/5X,'WL3 = ',F12.4,
C    ' MICRONS')
  IF (IFLAG.EQ.1) THEN
    READ(14,*) EMIS,TS,TF
    WRITE(18,12) EMIS,TS,TF
    WRITE(*,12) EMIS,TS,TF
12  FORMAT(1X,4X/5X,'EMIS = ',F14.2/5X,'TS = ',F14.1,' K'
C    /5X,'TF = ',F14.1,' K')
    R1 = RAD(EMIS,TS,TF,WL1,C1,C2)
    R2 = RAD(EMIS,TS,TF,WL2,C1,C2)
    R3 = RAD(EMIS,TS,TF,WL3,C1,C2)
    WRITE(18,13) R1,R2,R3
    WRITE(*,13) R1,R2,R3
13  FORMAT(1X,4X/5X,'R1 = ',E14.5,' W/M^2·MICRON'/5X,'R2 = ',
C    E14.5,' W/M^2·MICRON'/5X,'R3 = ',E14.5,' W/M^2·MICRON')
    BRT11 = BRT(R1,WL1,C1,C2)
    BRT12 = BRT(R2,WL2,C1,C2)
    BRT13 = BRT(R3,WL3,C1,C2)
    WRITE(18,17) BRT11,BRT12,BRT13
    WRITE(*,17) BRT11,BRT12,BRT13
17  FORMAT(1X,4X/5X,'BRT1 = ',F14.1,' K'/5X,'BRT2 = ',
C    F14.1,' K'/5X,'BRT3 = ',F14.1,' K')
    GO TO 155
  ELSE IF (IFLAG.EQ.2) THEN
    READ(14,*) EMIS0,TS0,TF0,EPS,IMAX,DELTA
    WRITE(18,14) EMIS0,TS0,TF0,EPS,IMAX,DELTA
    WRITE(*,14) EMIS0,TS0,TF0,EPS,IMAX,DELTA
14  FORMAT(1X,4X/5X,'EMIS0 = ',E14.2/5X,'TS0 = ',F14.1,' K'/5X,
C    'TF0 = ',F14.1,' K'/5X,'EPS = ',E14.5,' W/M^2'
C    /5X,'IMAX = ',I6/5X,'DELTA = ',F12.4)
    DO 111 L=1,N
    READ(14,*) ERR(L),BRT1(L),BRT2(L),BRT3(L)
111  CONTINUE
    WRITE(18,16)
    WRITE(*,16)
16  FORMAT(4X,'ERR',6X,'BRT1',6X,'BRT2',6X,'BRT3',6X,'EMIS',6X,
C    'TS',6X,'TF',10X,'I')
    DO 500 K=1,N
      EMIS=EMIS0
      TS=TS0
      TF=TF0
      E1 = EBL(BRT1(K),WL1,C1,C2)
      E2 = EBL(BRT2(K),WL2,C1,C2)
      E3 = EBL(BRT3(K),WL3,C1,C2)
      E1 = E1-RAD(EMIS,TS,TF,WL1,C1,C2)
      E2 = E2-RAD(EMIS,TS,TF,WL2,C1,C2)
      E3 = E3-RAD(EMIS,TS,TF,WL3,C1,C2)
      DO 20 I=1,IMAX
        OEM = EMIS
        OTS = TS
        OTF = TF
        A11 = EBL(TS,WL1,C1,C2)-EBL(TF,WL1,C1,C2)
        A12 = EMIS*DEDT(TS,WL1,C1,C2)
        A13 = (1-EMIS)*DEDT(TF,WL1,C1,C2)
        A21 = EBL(TS,WL2,C1,C2)-EBL(TF,WL2,C1,C2)

```

- 52 -

```

      A22 = EMIS*DEDT(TS,WL2,C1,C2)
      A23 = (1-EMIS)*DEDT(TF,WL2,C1,C2)
      A31 = EBL(TS,WL3,C1,C2)-EBL(TF,WL3,C1,C2)
      A32 = EMIS*DEDT(TS,WL3,C1,C2)
      A33 = (1-EMIS)*DEDT(TF,WL3,C1,C2)
      DETJ1 = A11*A22*A33+A12*A23*A31+A13*A21*A32
      DETJ2 = A13*A22*A31+A12*A21*A33+A11*A23*A32
      DETJ = DETJ1-DEJ2
      IF (DEJ.EQ.0.) THEN
        WRITE(18,23) K,I
        WRITE(*,23) K,I
23      FORMAT(1X,4X,'JACOBIAN IS SINGULAR AND ( K,I ) =
      C      (' ,I4,' ,',I4,' )')
        GO TO 100
*23456789012345678901234567890123456789012345678901234567890123456789012
      ENDIF
      DE1 = B1*A22*A33+A12*A23*B3+A13*B2*A32
      DE2 = A13*A22*B3+A12*B2*A33+B1*A23*A32
      DE = (DE1-DE2)/DEJ
      DS1 = A11*B2*A33+B1*A23*A31+A13*A21*B3
      DS2 = A13*B2*A31+B1*A21*A33+A11*A23*B3
      DS = (DS1-DS2)/DEJ
      DF1 = A11*A22*B3+A12*B2*A31+B1*A21*A32
      DF2 = B1*A22*A31+A12*A21*B3+A11*B2*A32
      DF = (DF1-DF2)/DEJ
      EMIS = OEM+DELTA*DE
      TS = OTS+DELTA*DS
      TF = OTF+DELTA*DF
      B1 = R1-RAD(EMIS,TS,TF,WL1,C1,C2)
      B2 = R2-RAD(EMIS,TS,TF,WL2,C1,C2)
      B3 = R3-RAD(EMIS,TS,TF,WL3,C1,C2)
      TEST = SQRT(B1*B1+B2*B2+B3*B3)
      IF (TEST.LE.EPS) GO TO 99
20      CONTINUE
      ELSE
        WRITE(*,21)
        WRITE(18,21)
21      FORMAT(1X,4X,'INAPPROPRIATE VALUE OF IFLAG.')
        GO TO 155
      ENDIF
      WRITE(18,15) K,I
      WRITE(*,15) K,I
15      FORMAT(1X,4X,'IMAX EXCEEDED WITHOUT CONVERGENCE AND
      C (K,I) = (' ,I4,' ,',I4,' )')
        GO TO 100
99      CONTINUE
      WRITE(*,19) ERR(K),BRT1(K),BRT2(K),BRT3(K),EMIS,TS,TF,I
      WRITE(18,19) ERR(K),BRT1(K),BRT2(K),BRT3(K),EMIS,TS,TF,I
19      FORMAT(1X,F8.1,2X,F8.1,2X,F8.1,2X,F8.1,2X,F6.4,2X,F8.1,
      C      2X,F8.1,2X,I6)
100     CONTINUE
500     CONTINUE
155     CONTINUE
      CLOSE(18)
      PAUSE
      STOP
      END
*23456789012345678901234567890123456789012345678901234567890123456789012
*.....
*.....
      FUNCTION RAD(EMIS,TS,TF,WL,C1,C2)
      RAD = (1.-EMIS)*EBL(TF,WL,C1,C2)+EMIS*EBL(TS,WL,C1,C2)
      RETURN
      END

```

- 53 -

```

*.....
      FUNCTION EBL(T,WL,C1,C2)
      EBL = C1/(WL**5*(EXP(C2/(WL*T))-1.))
      RETURN
      END

*.....
      FUNCTION BRT(R,WL,C1,C2)
      BRT = C2/(WL*ALOG((C1/(R*WL**5)+1.)))
      RETURN
      END

*.....
      FUNCTION DEDT(T,WL,C1,C2)
      DEDT = C1*C2*EXP(C2/(WL*T))/(WL**6*T*(EXP(C2/(WL*T))-1.))**2
      RETURN
      END

*.....
*.....
*23456789012345678901234567890123456789012345678901234567890123456789012

```

## (2) A sample input file:

```

11
1
0.8D0
1.6D0
2.2D0
0.4D0
1300.D0
1500.D0
1.D-1
1000
1.D0
-5.00 1450.3 1434.1 1424.0
-4.00 1450.3 1434.1 1425.0
-3.00 1450.3 1434.1 1426.0
-2.00 1450.3 1434.1 1427.0
-1.00 1450.3 1434.1 1428.0
0.00 1450.3 1434.1 1429.0
1.00 1450.3 1434.1 1430.0
2.00 1450.3 1434.1 1431.0
3.00 1450.3 1434.1 1432.0
4.00 1450.3 1434.1 1433.0
5.00 1450.3 1434.1 1434.0

```

## (3) A sample output file:

```

N = 11
IFLAG = 2
WL1 = .8000 MICRONS
WL2 = 1.6000 MICRONS
WL3 = 2.2000 MICRONS

EMISO = 0.40E+00
TS0 = 1200.0 K
TF0 = 1600.0 K
EPS = 0.10000E+00 W/M^2
IMAX = 1000

```

- 54 -

DELTA = 1.0000

ERR	BRT1	BRT2	BRT3	EMIS	TS	TF	I
-5.0	1450.3	1434.1	1424.0	.1360	885.3	1467.6	6
-4.0	1450.3	1434.1	1425.0	.1445	979.0	1468.7	6
-3.0	1450.3	1434.1	1426.0	.1602	1060.8	1470.8	6
-2.0	1450.3	1434.1	1427.0	.1901	1139.5	1474.6	5
-1.0	1450.3	1434.1	1428.0	.2525	1219.3	1482.2	5
.0	1450.3	1434.1	1429.0	.3994	1299.9	1499.9	5
1.0	1450.3	1434.1	1430.0	.6979	1369.5	1548.6	4
2.0	1450.3	1434.1	1431.0	.9280	1408.3	1666.0	11
3.0	1450.3	1434.1	1432.0	.9879	1424.1	1887.9	13
4.0	1450.3	1434.1	1433.0	.9987	1430.9	2374.0	10

JACOBIAN IS SINGULAR AND ( K,I ) = ( 11, 7)

- 55 -

CLAIMSWhat is claimed is:

1. A method of measuring the temperature of a surface, said method comprising:
  - 5 providing a surface;
  - selecting a first wave length;
  - providing a first pyrometer;
  - adapting said first pyrometer to sense radiation of said first wave length;
  - selecting a second wave length;
  - 10 providing a second pyrometer;
  - adapting said second pyrometer to sense radiation of said second wave length;
  - focussing said first pyrometer on said surface and obtaining a first reading;
  - focussing said second pyrometer on said surface and obtaining a second reading;
  - determining an emissivity of said surface; and
  - 15 determining said temperature by utilizing said first reading; said second reading and said emissivity.
2. The method of claim 1 further comprising positioning said surface within an enclosure prior to said focussing of said first pyrometer on said surface.
- 20 3. The method of claim 1 further comprising selecting said first wave length to be within the range of 0.5 to 5 microns.
4. The method of claim 1 further comprising selecting said second wave  
25 length to be within the range of 0.5 to 5 microns.
5. The method of claim 1 further comprising determining said emissivity by:
  - insulating said surface;
  - 30 heating said surface;
  - focussing a third pyrometer on said surface;
  - obtaining readings from said third pyrometer as said surface cools; and
  - determining said emissivity by utilizing said readings from said third pyrometer.

- 56 -

6. The method of claim 1 further comprising adapting said first pyrometer to sense radiation of said first wave length by using a filter.

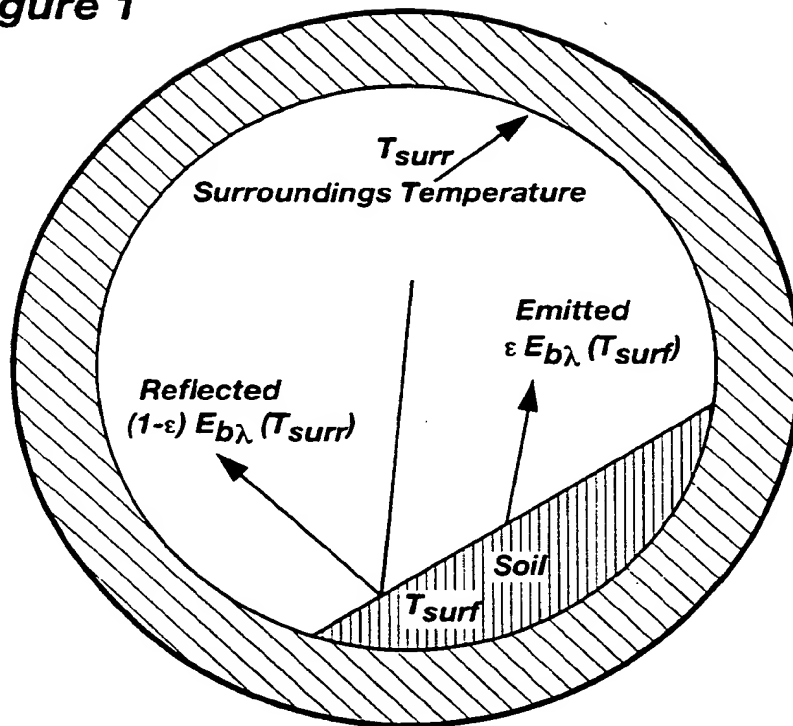
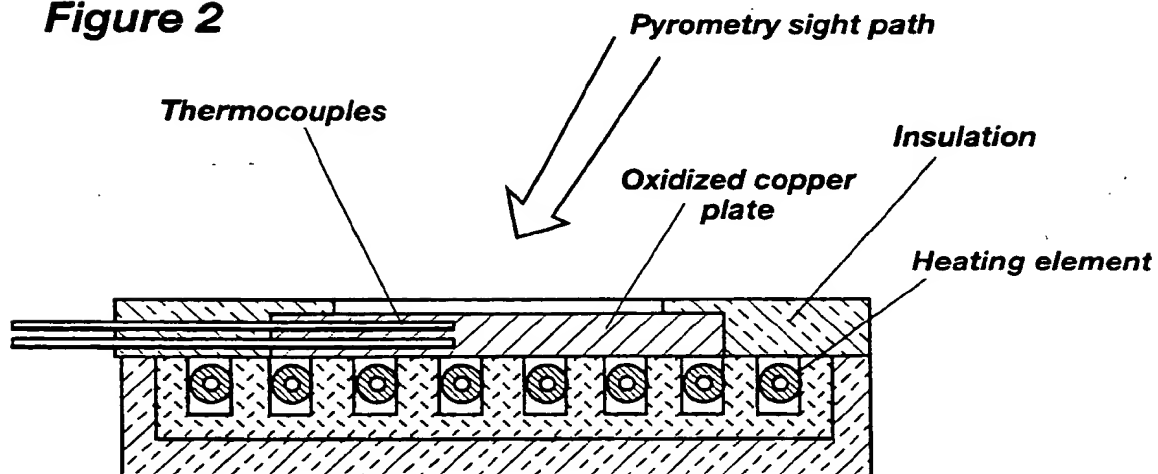
7. The method of claim 1 further comprising adapting said second  
5 pyrometer to sense radiation of said second wave length by using a filter.

8. The method of claim 1 wherein said first pyrometer and said second pyrometer are one and the same pyrometer.

10 9. The method of claim 1 wherein said first wave length is selected to minimize the effects of particulate material in the line of sight of said first pyrometer to said surface.

10. The method of claim 1 wherein said second wave length is selected to  
15 minimize the effects of particulate material in the line of sight of said second pyrometer to said surface.

11. The method of claim 1 further comprising:  
selecting a third wave length;  
20 providing a third pyrometer;  
adapting said third pyrometer to sense radiation having said third wave length; and  
focussing said third pyrometer on said surface and obtaining readings.

**Figure 1****Figure 2**

SUBSTITUTE SHEET (RULE 26)



2/23

Figure 3

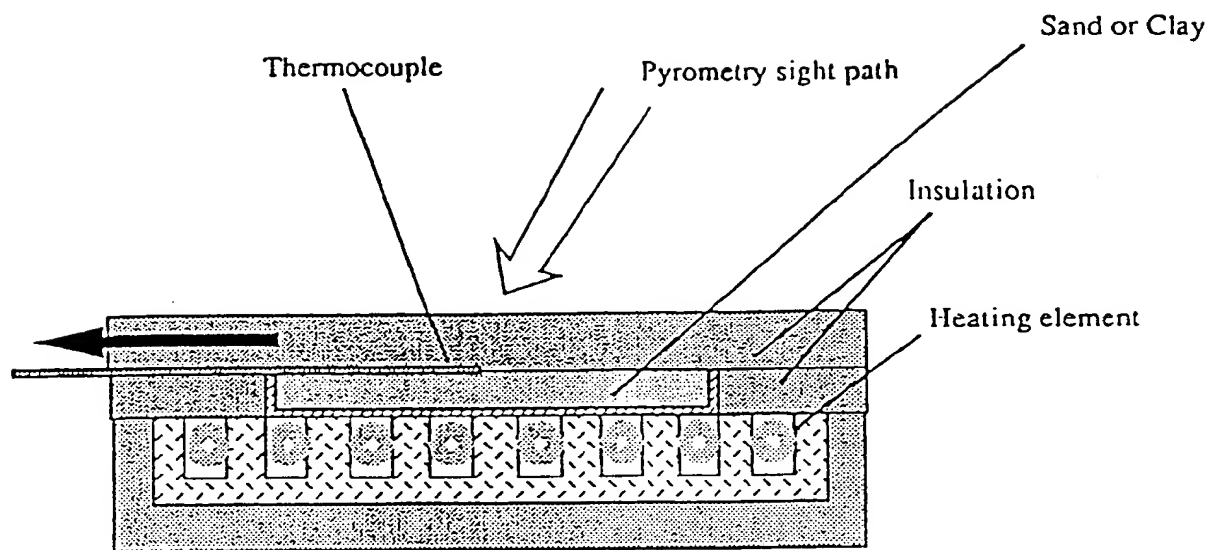


Figure 4 (TOP)

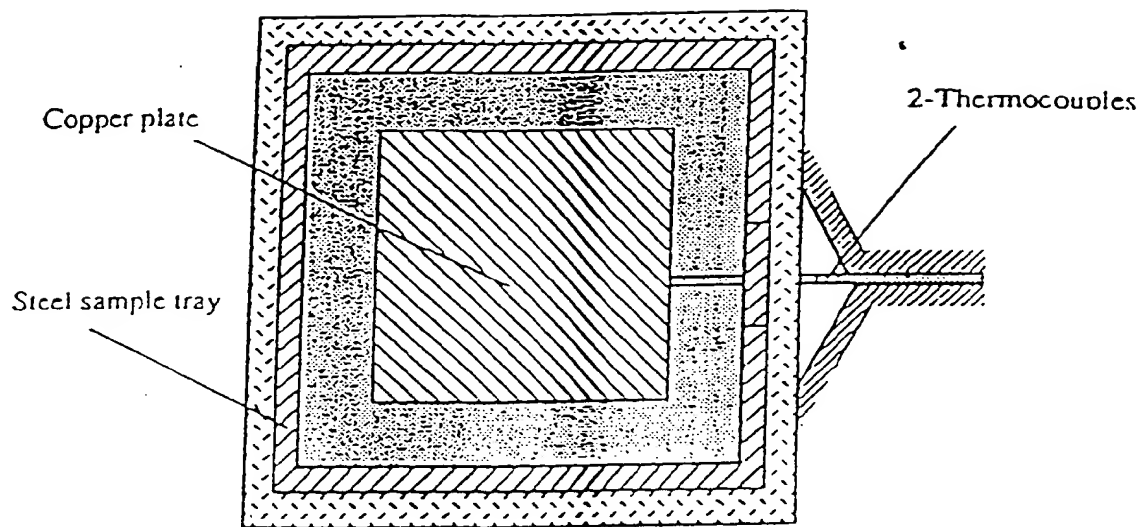
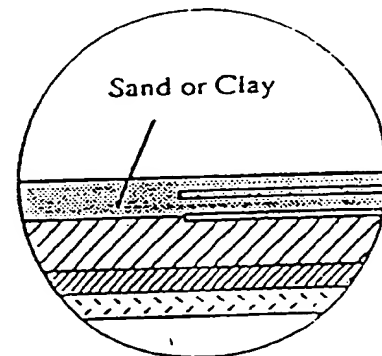
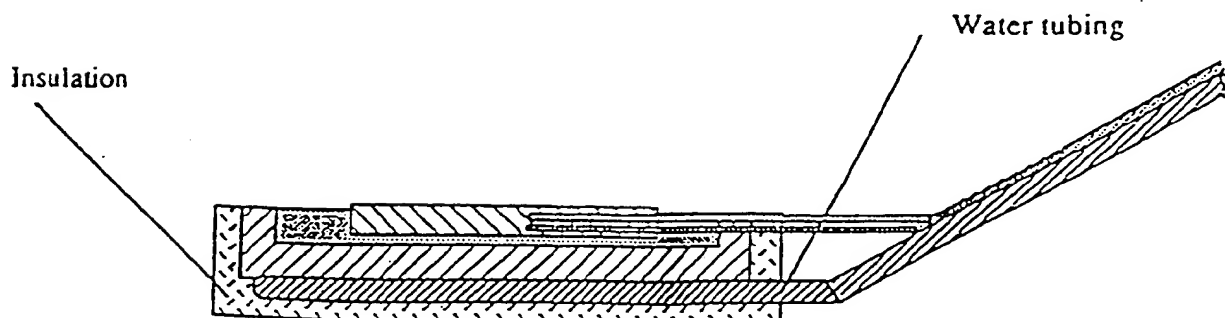
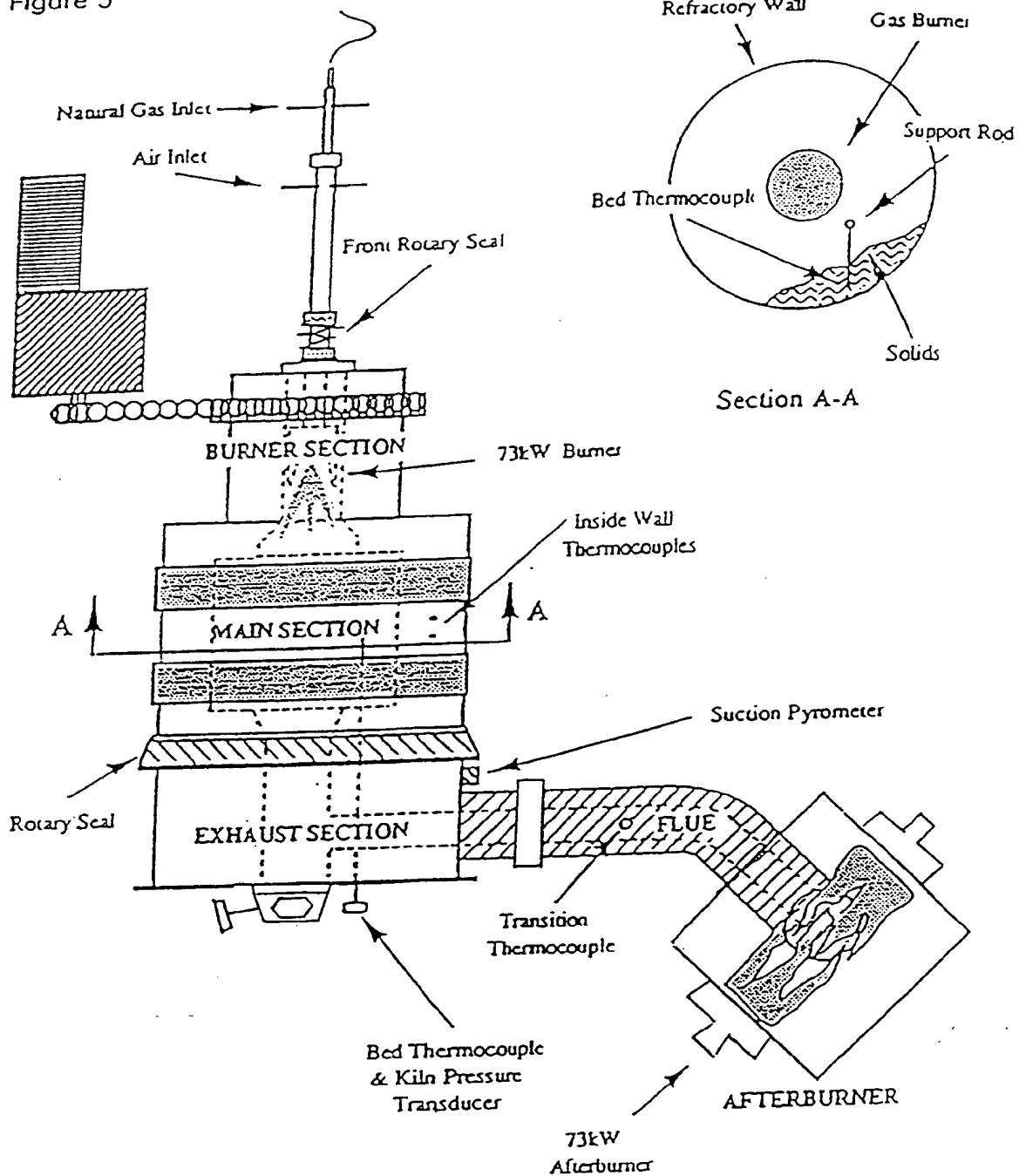


Figure 4A

Figure 4B  
(SIDE)

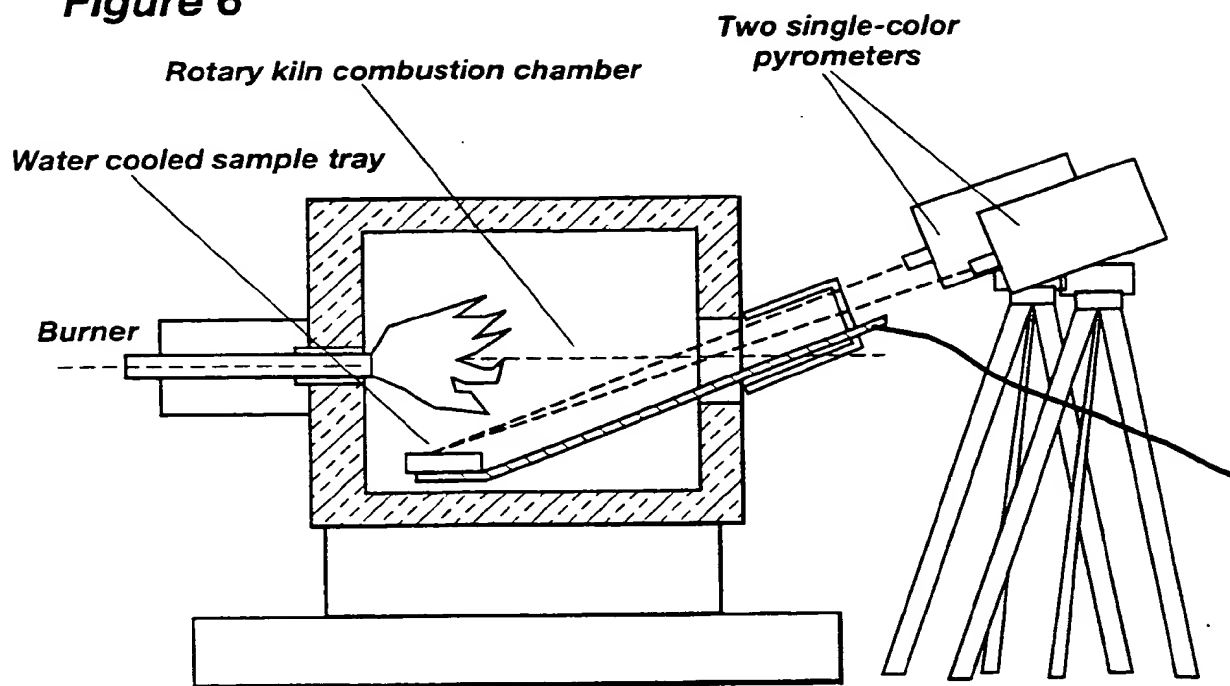
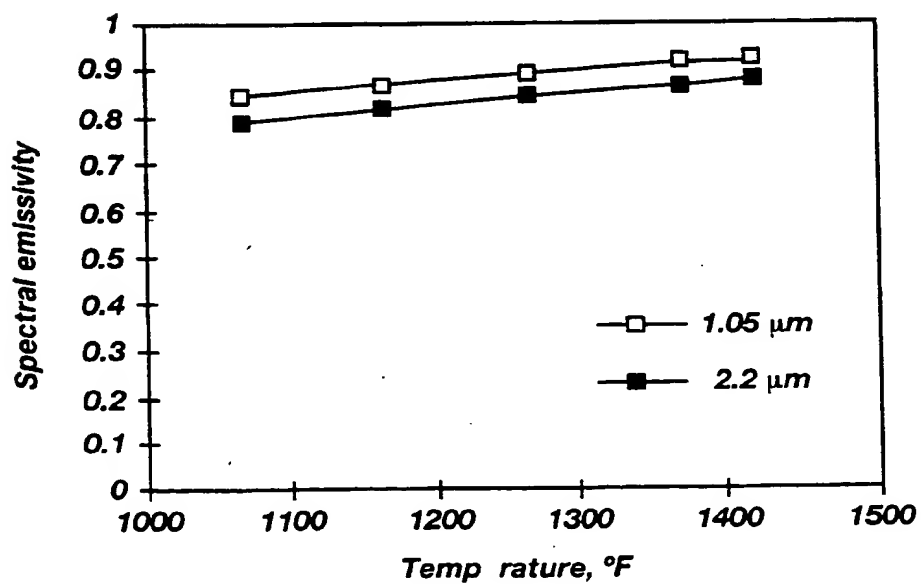
SUBSTITUTE SHEET (RULE 26)

Figure 5



SUBSTITUTE SHEET (RULE 26)

5/23

**Figure 6****Figure 7**

SUBSTITUTE SHEET (RULE 26)

6/23

Figure 8

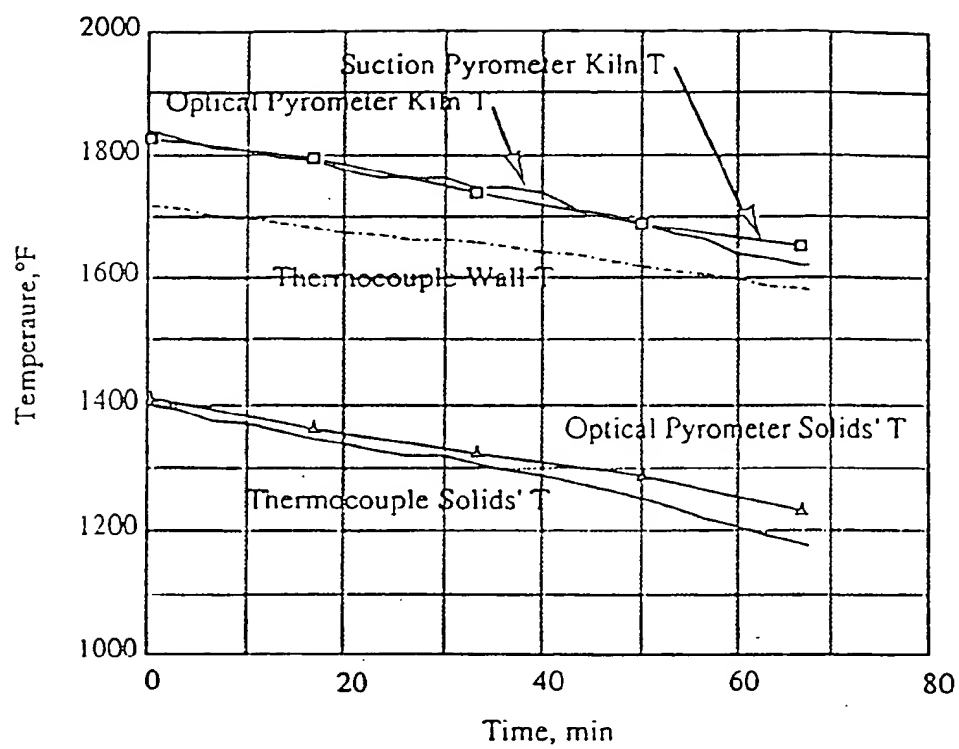
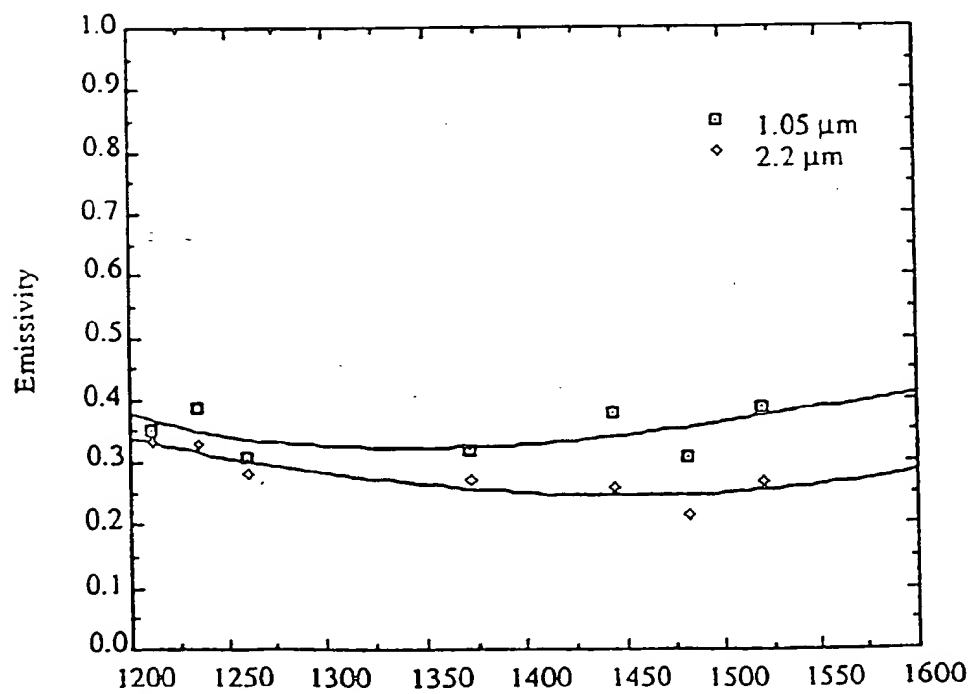


Figure 9



7/23

Figure 10

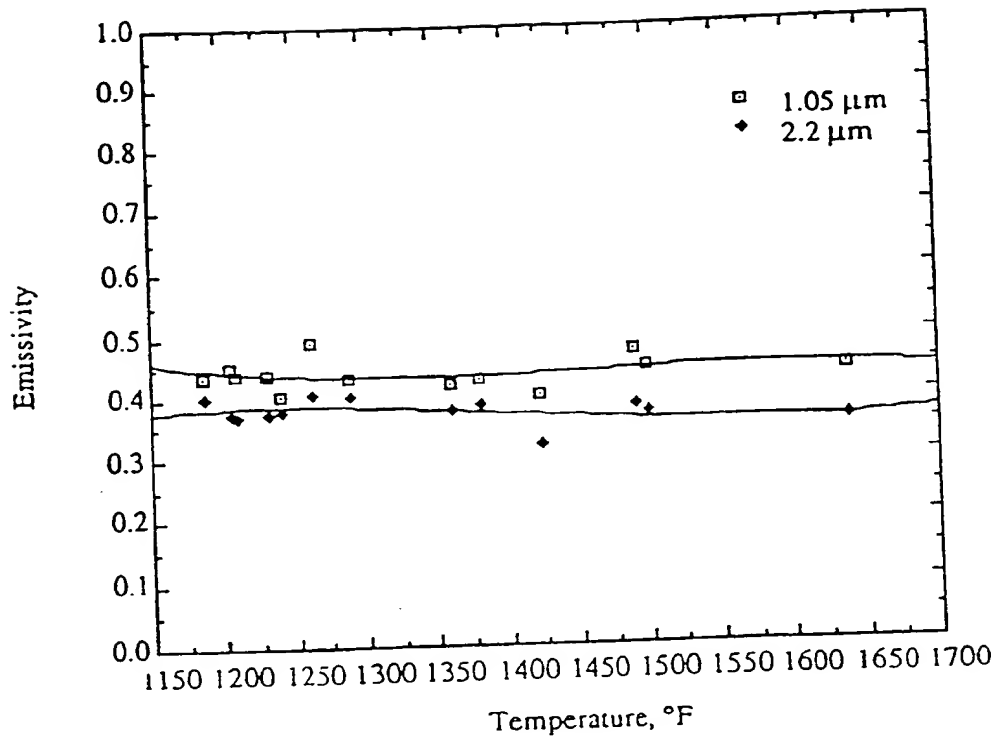


Figure 11

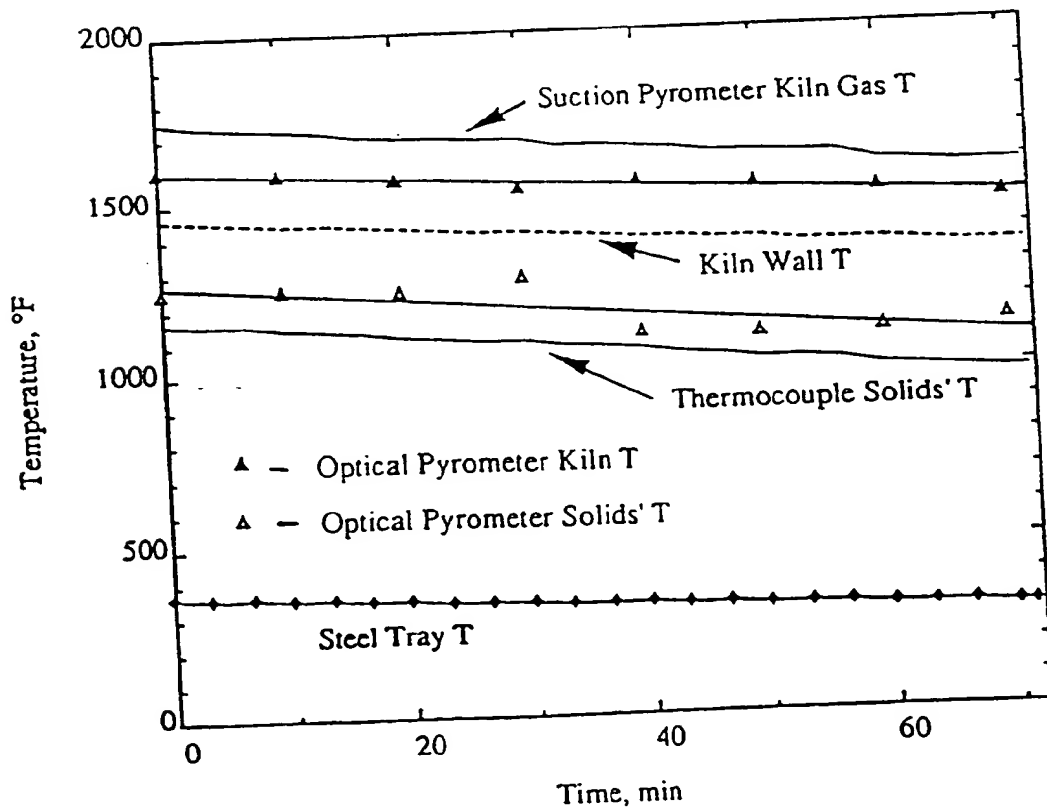


Figure 12

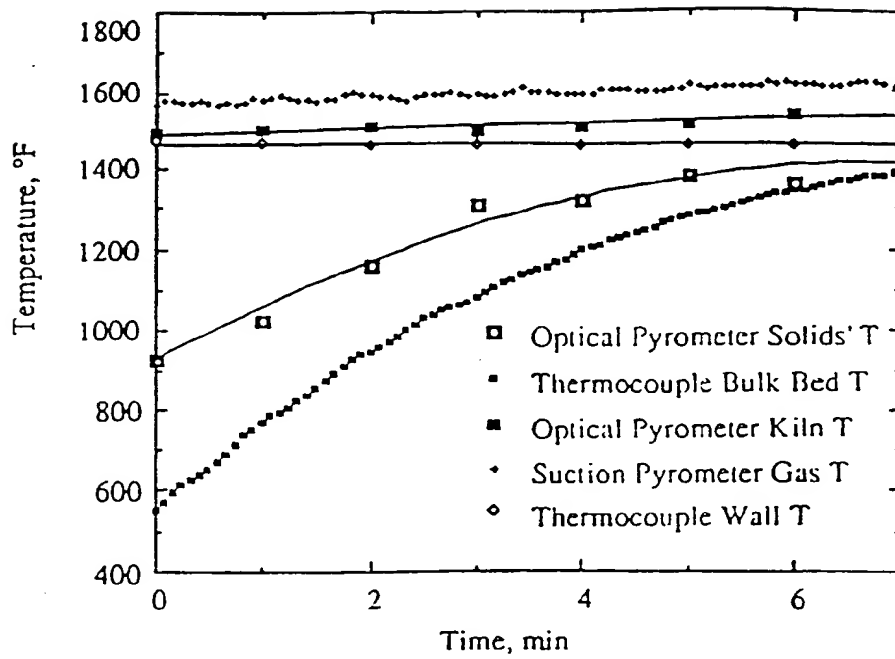
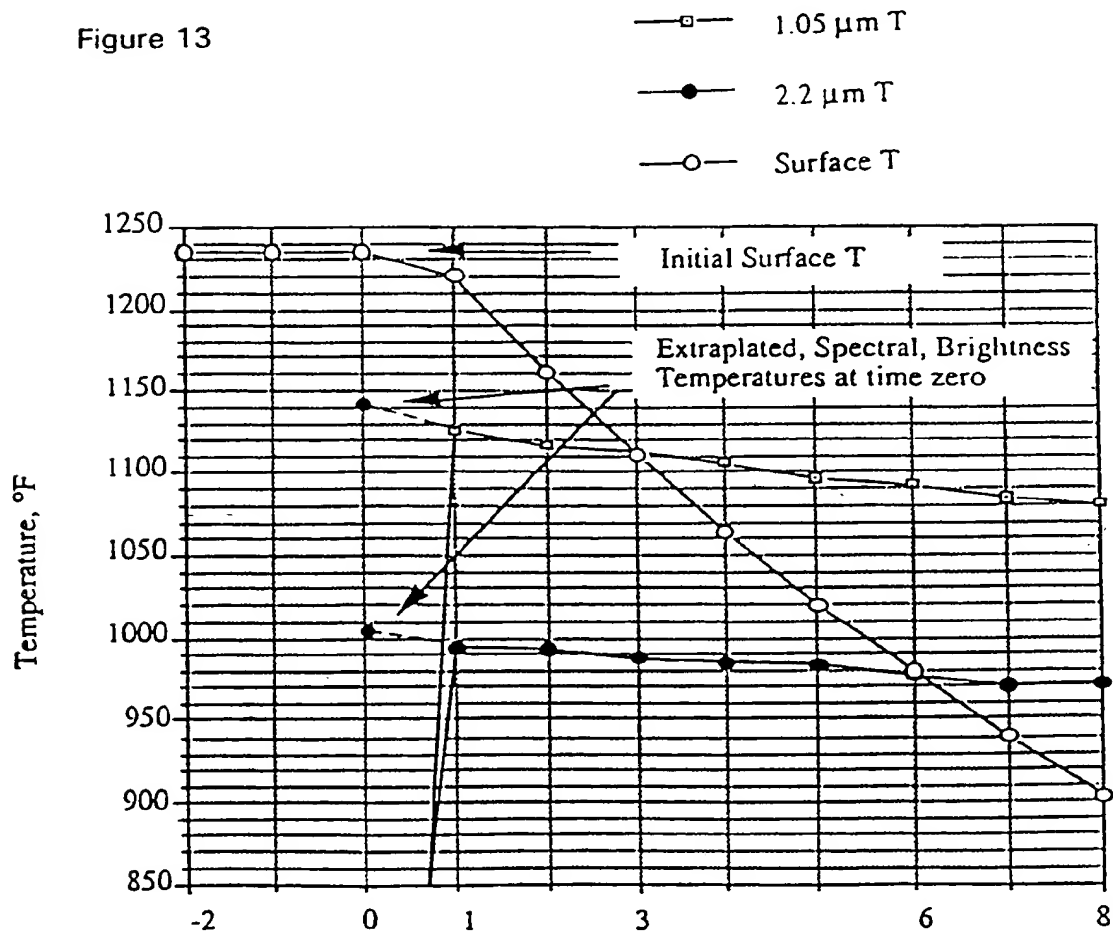
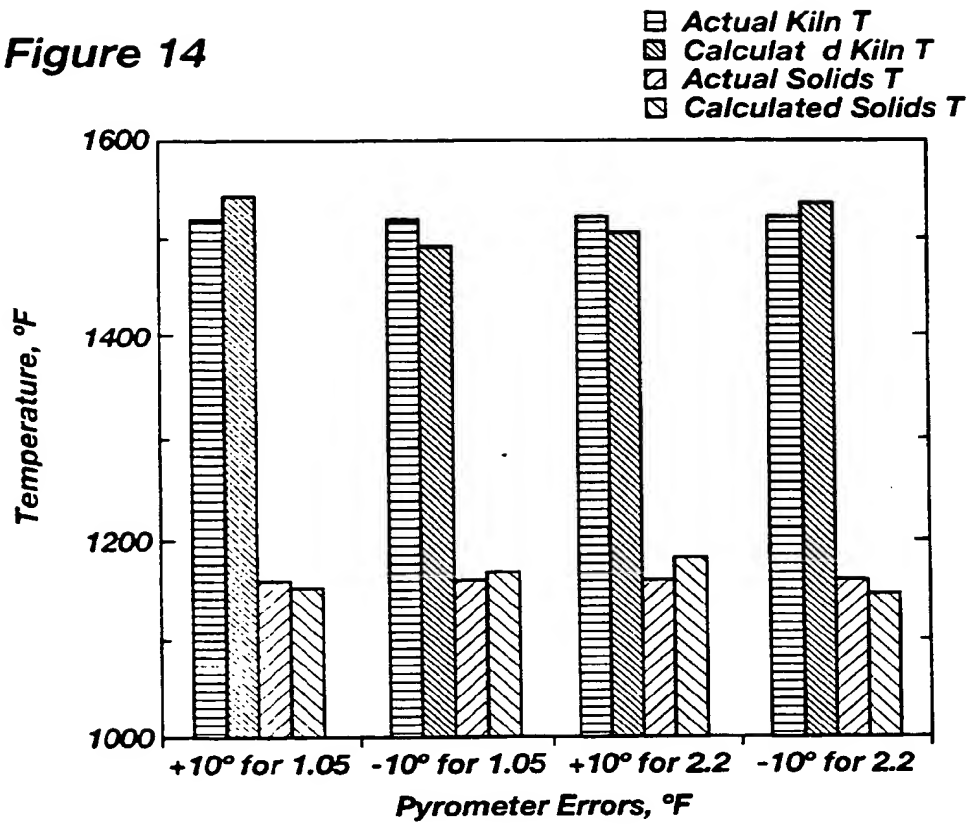
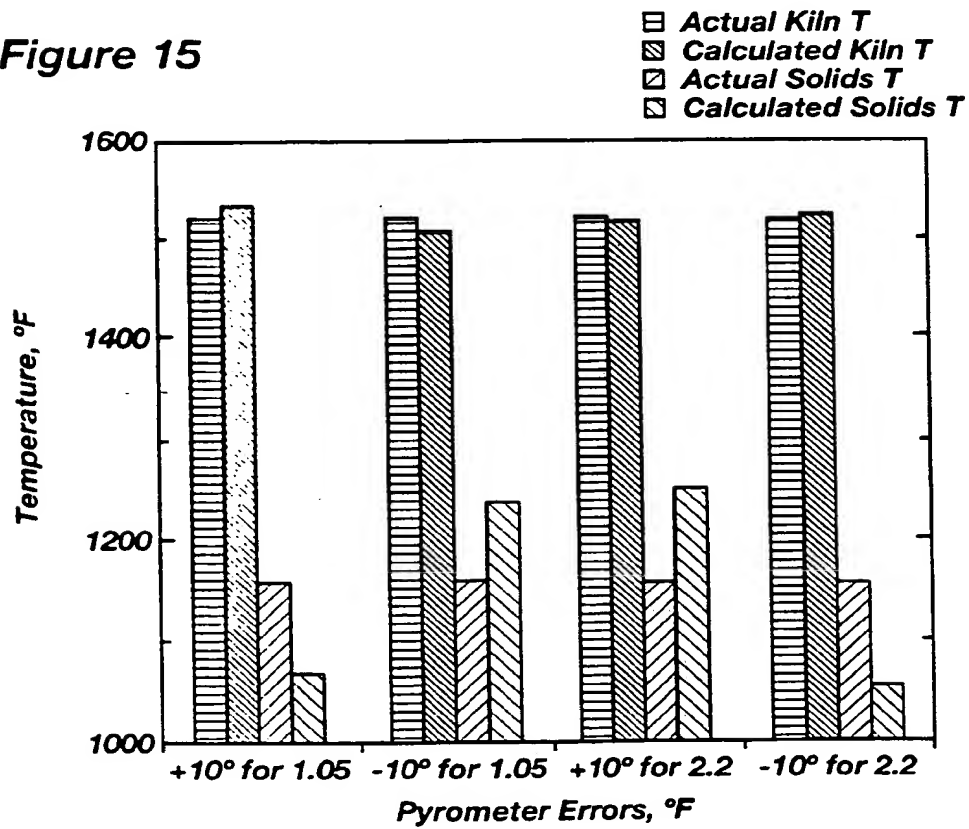


Figure 13



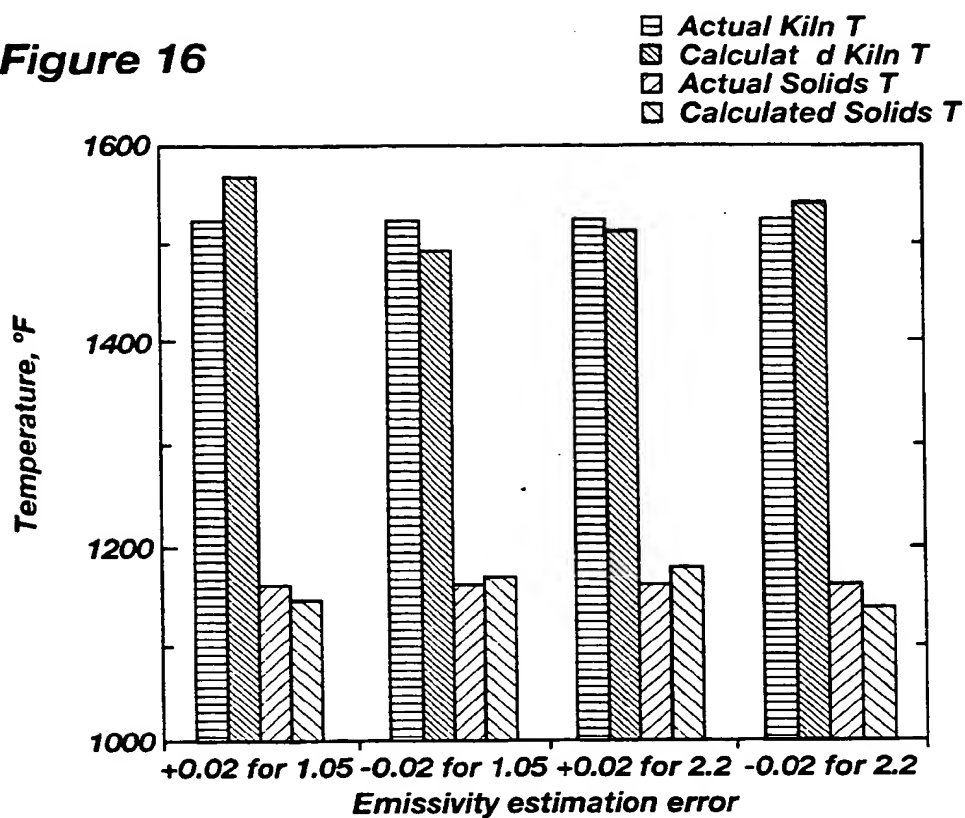
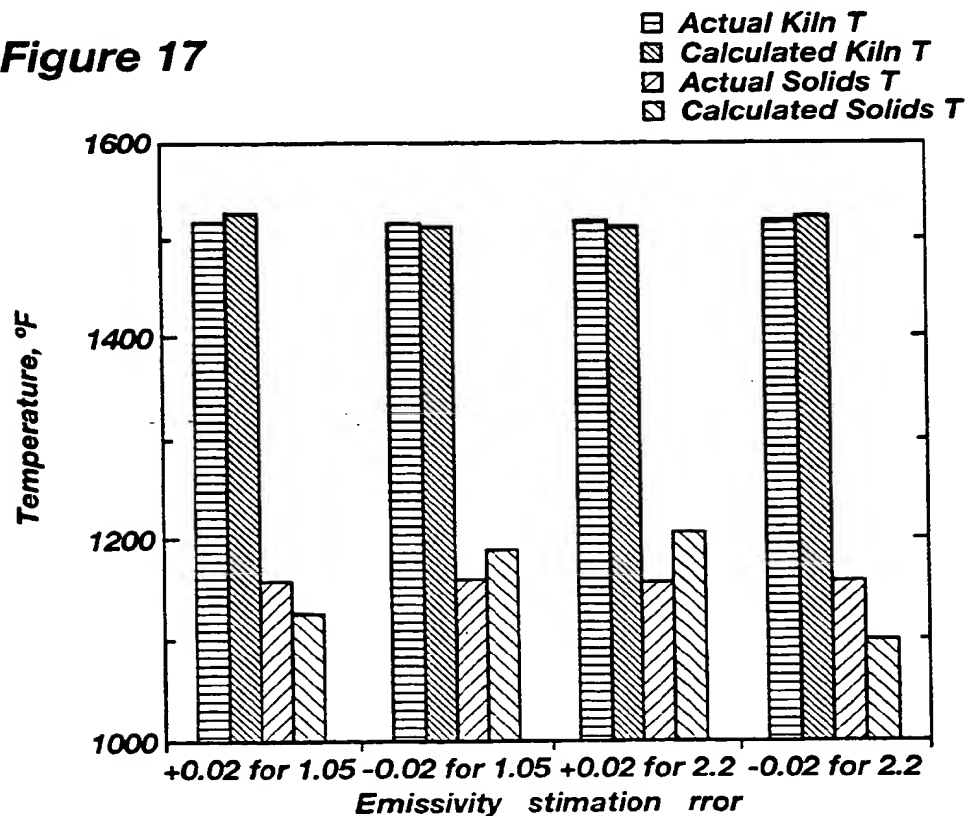
9/23

**Figure 14****Figure 15**

SUBSTITUTE SHEET (RULE 26)



10/23

**Figure 16****Figure 17**

SUBSTITUTE SHEET (RULE 26)

11/23

Figure 18

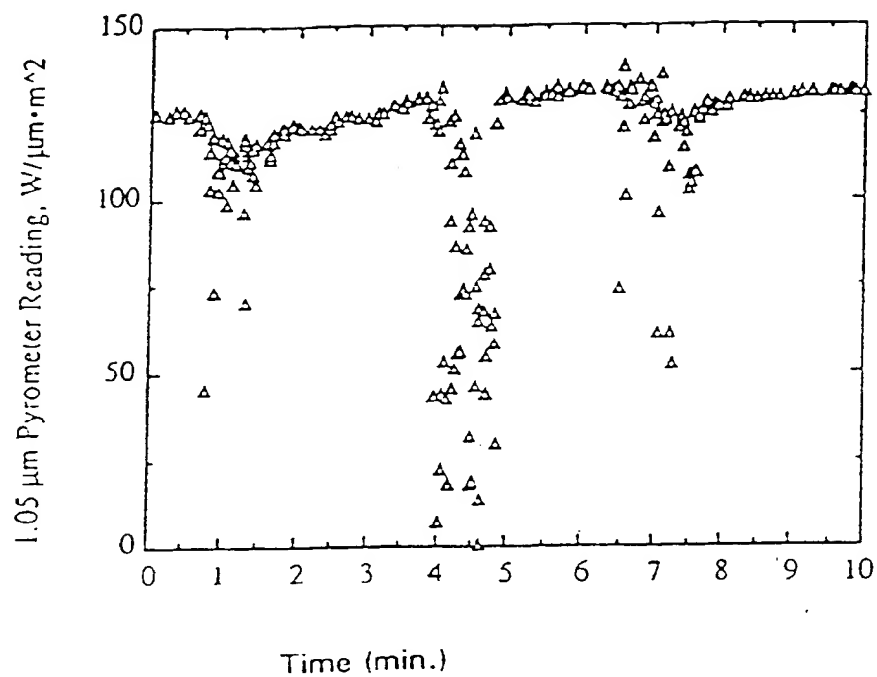
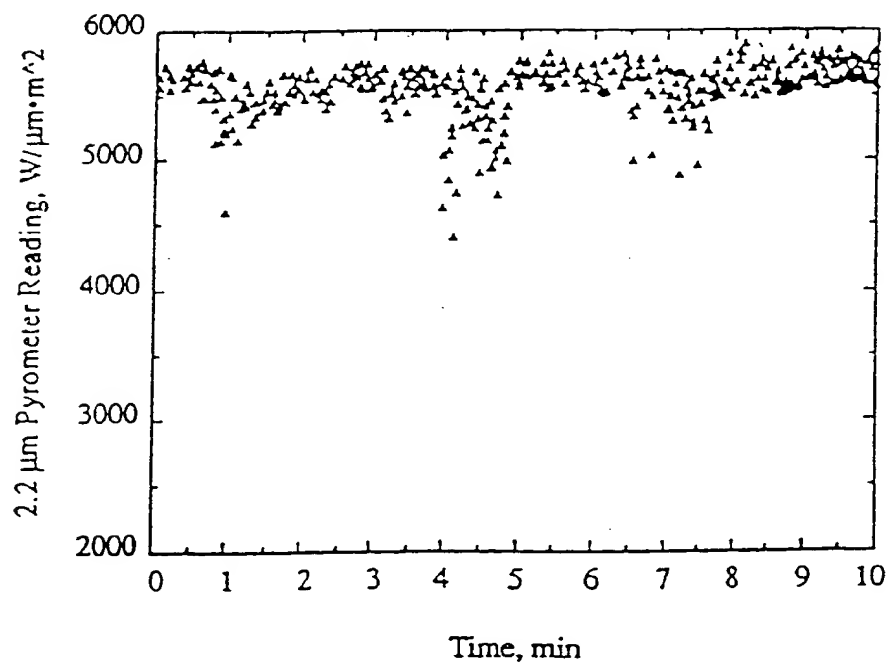


Figure 18A



SUBSTITUTE SHEET (RULE 26)

12/23

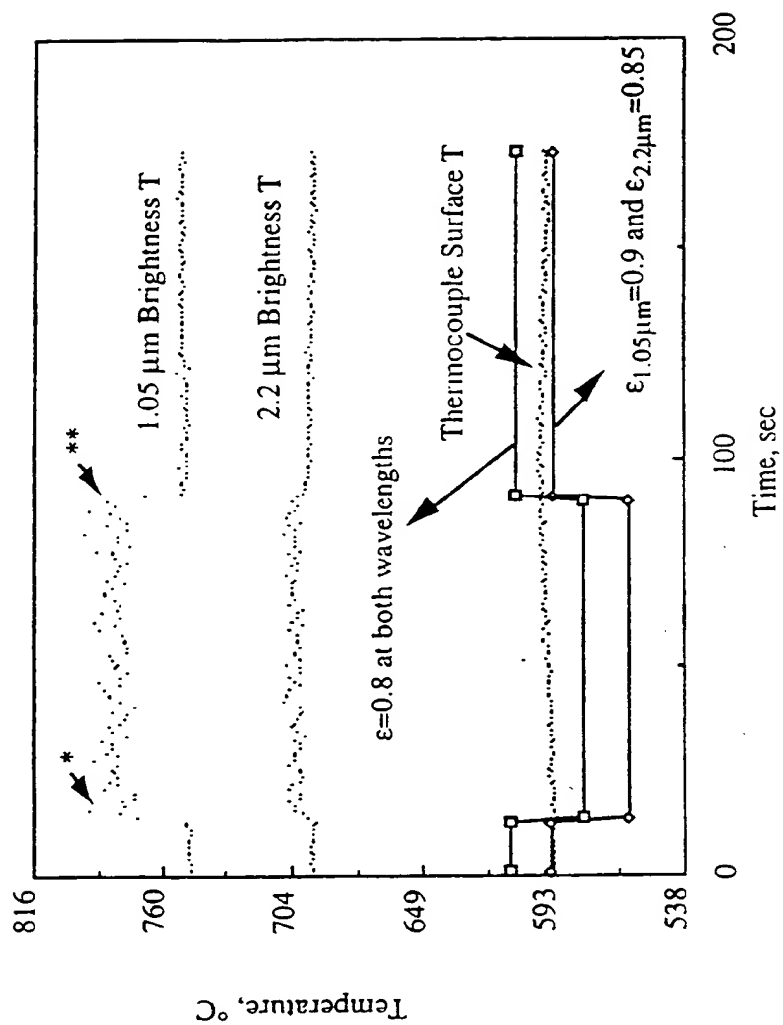


Figure 19

13/23

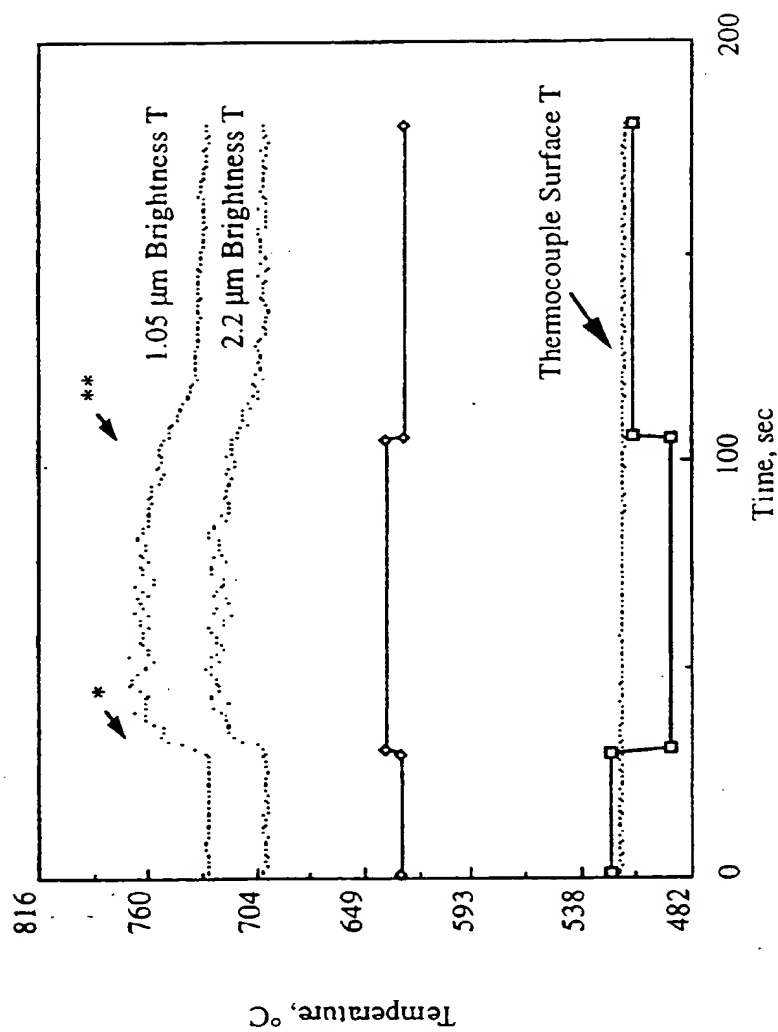


Figure 20

14/23

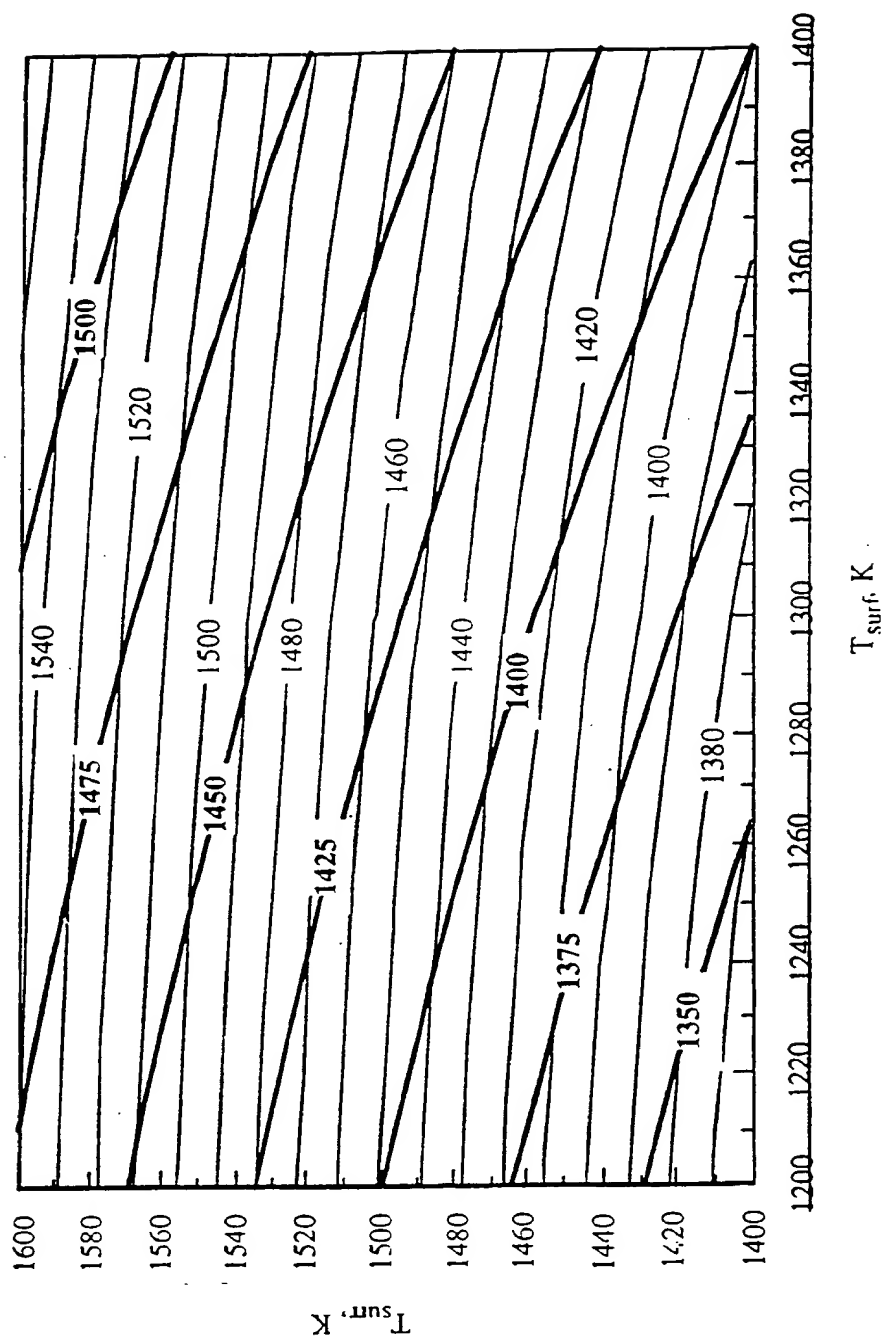


Figure 21

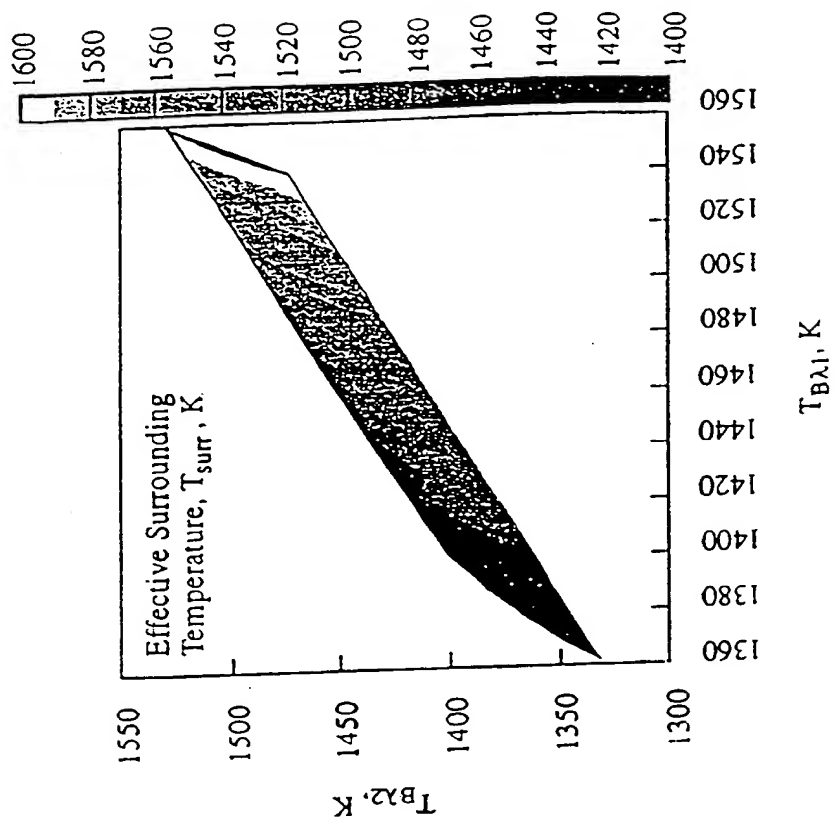


Figure 22A

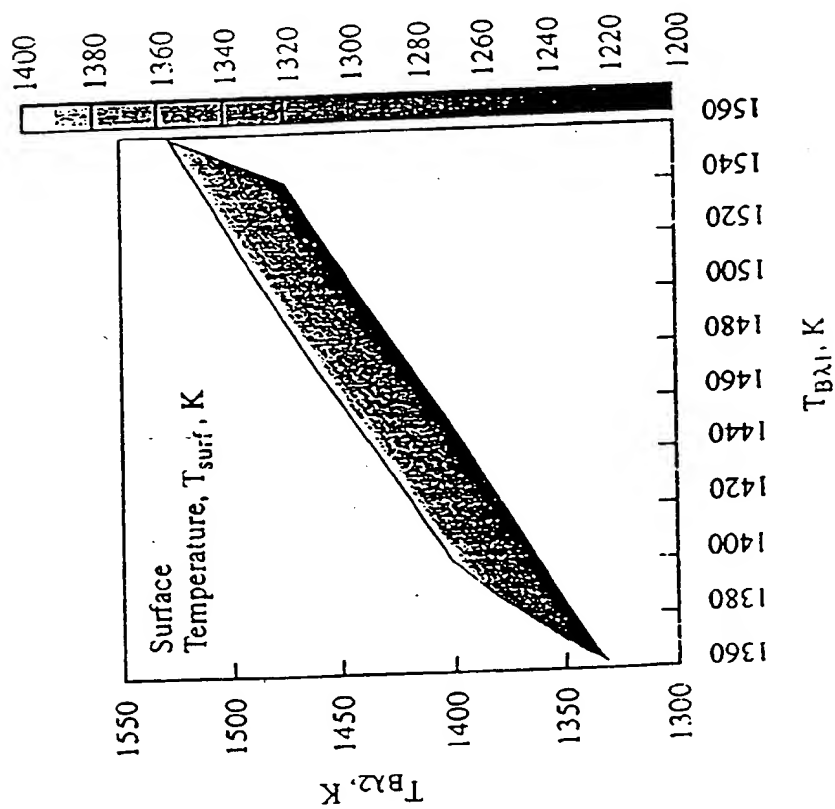


Figure 22

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16/23

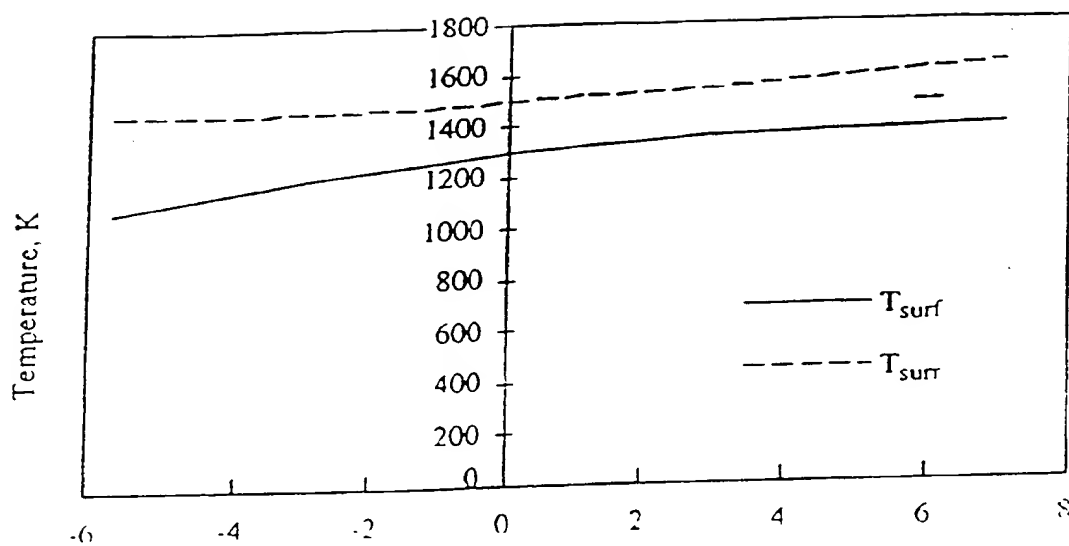


Figure 23A

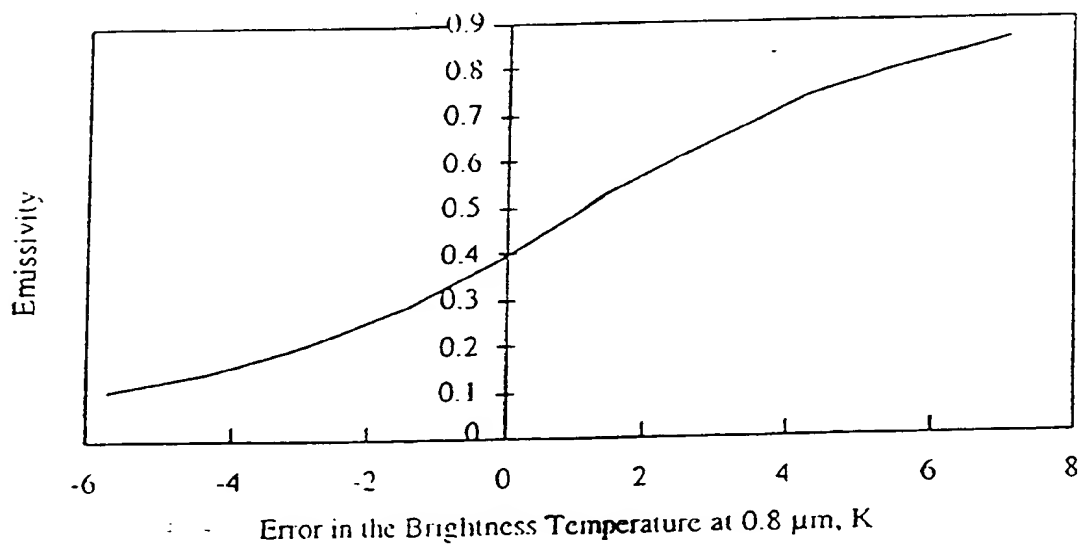


Figure 23

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17/23

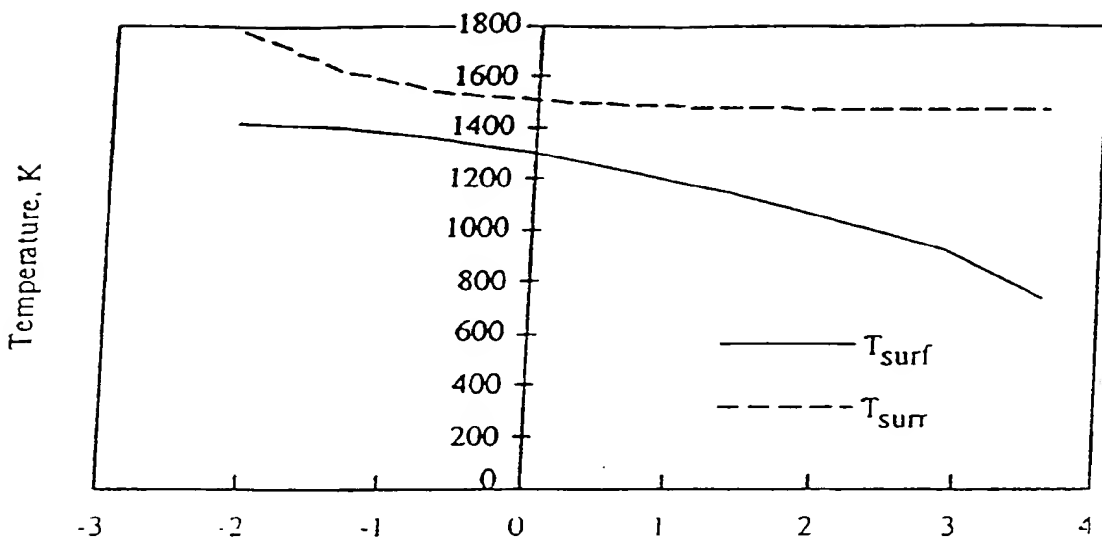


Figure 24A

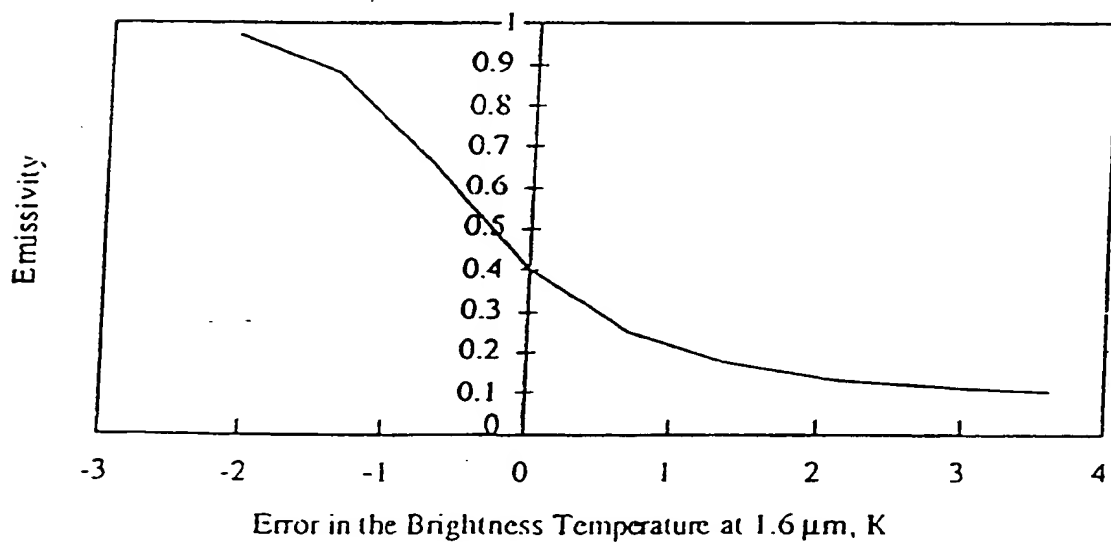


Figure 24

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18/23

Figure 25A

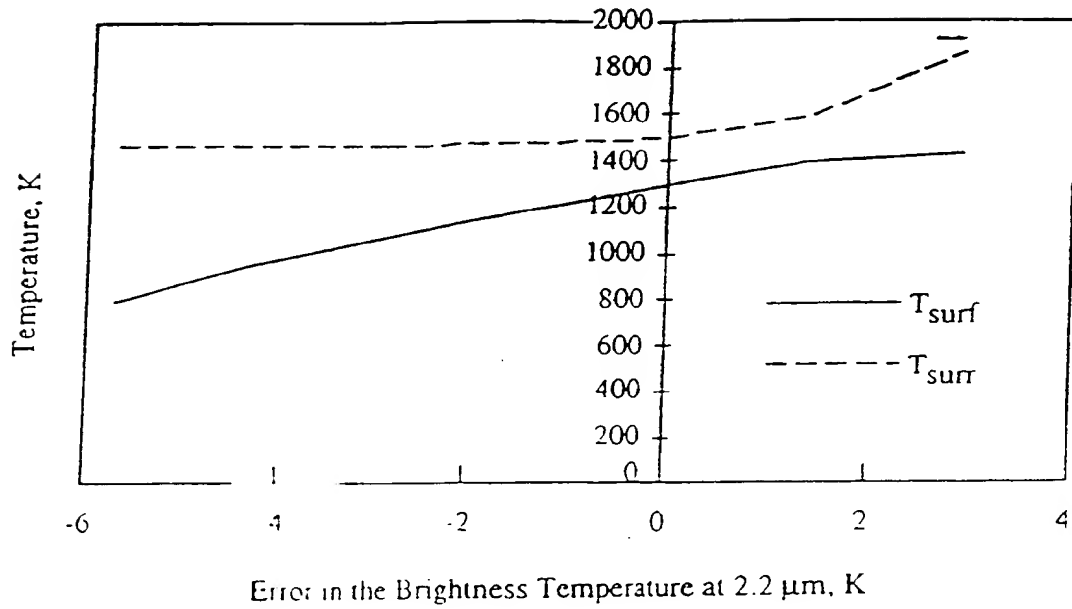
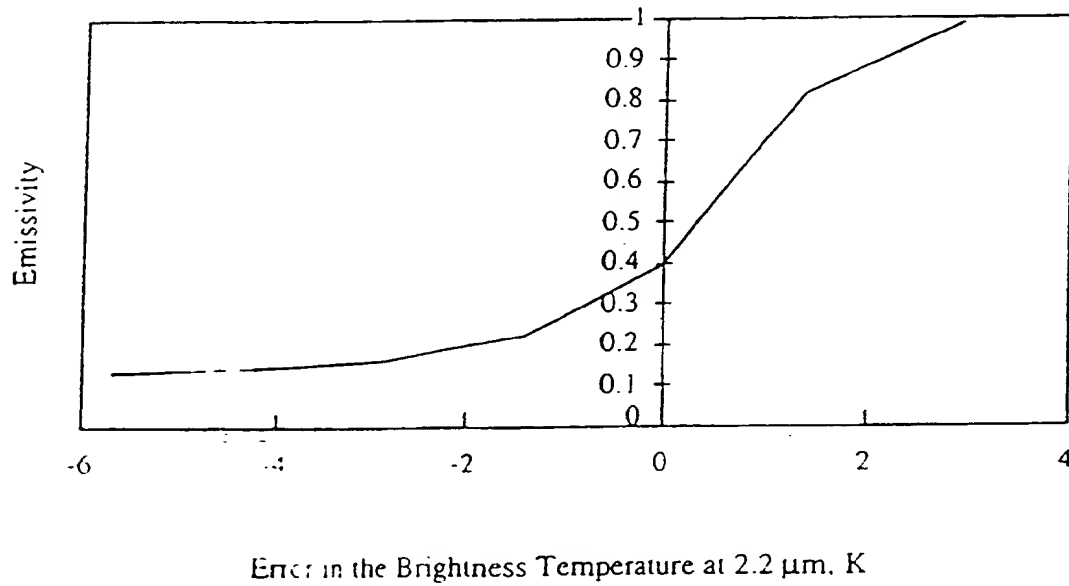


Figure 25



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19/23

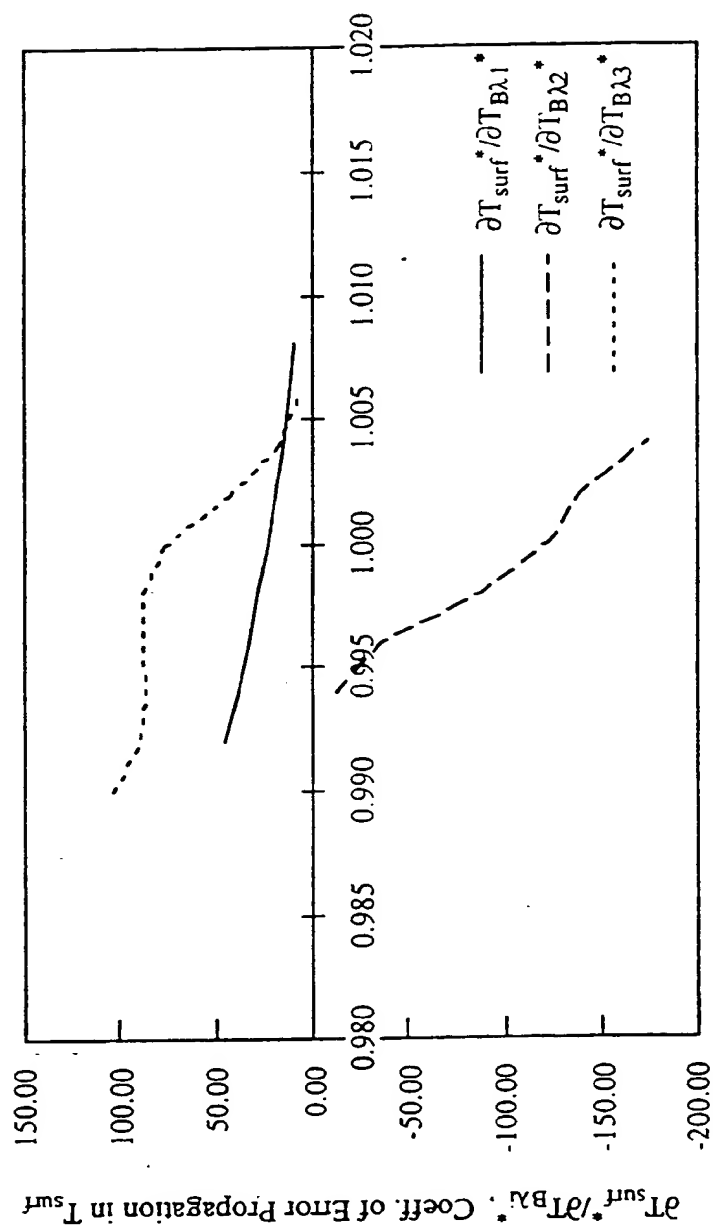
Normalized Brightness Temperature,  $(T_{B\lambda i} \pm j)/T_{B\lambda i}^\circ$ 

Figure 26

20/23

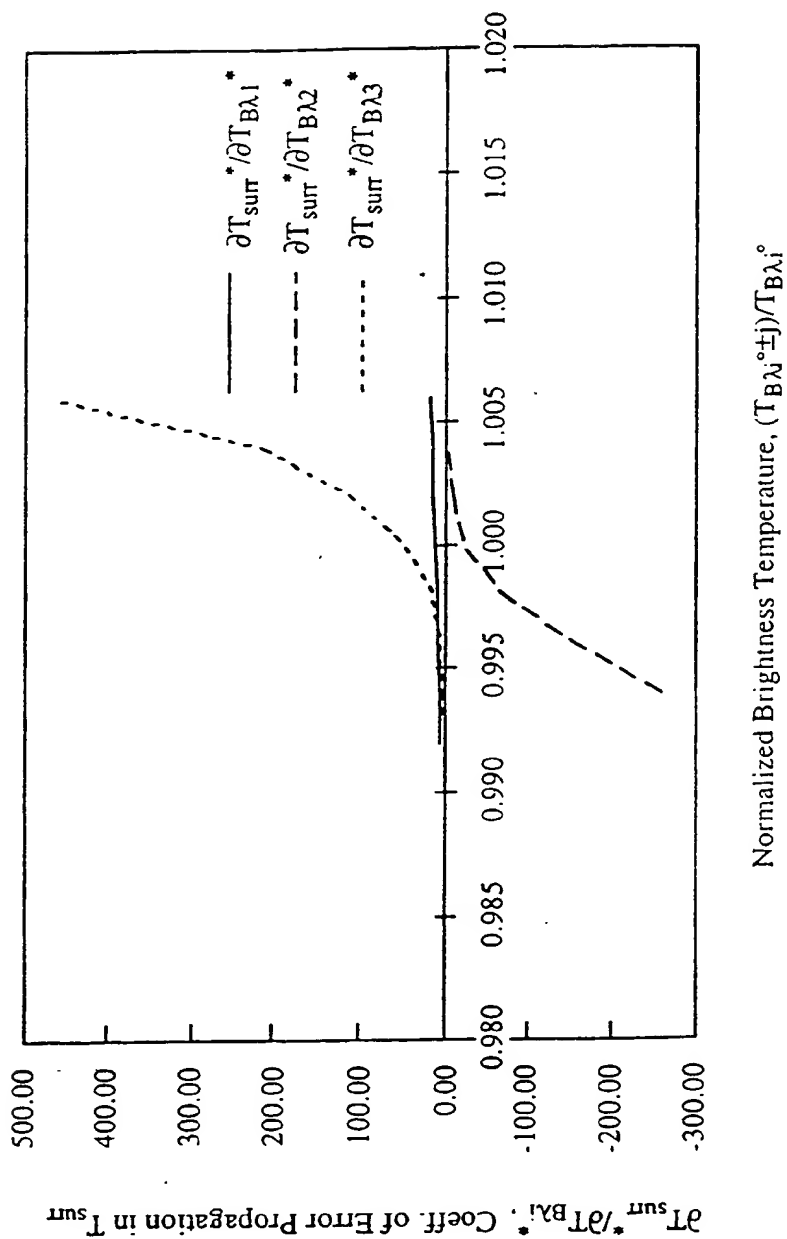


Figure 27

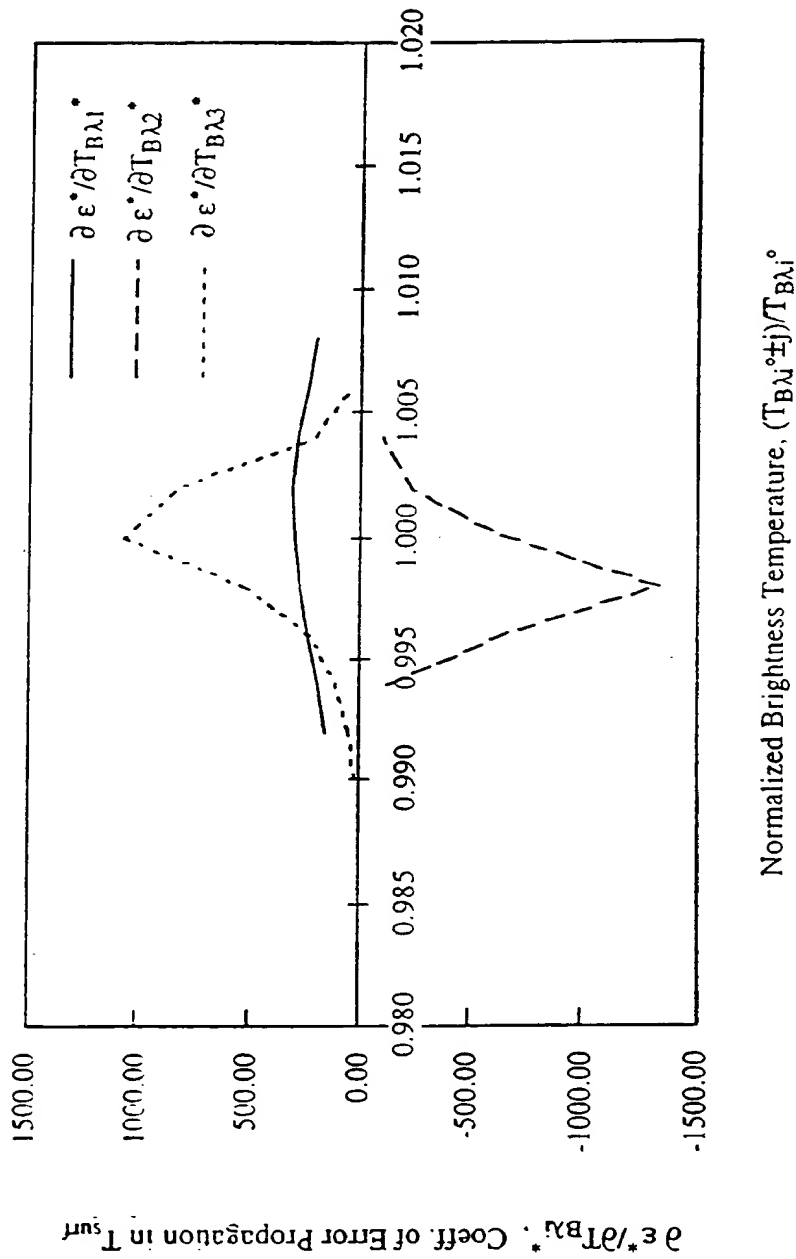


Figure 28

22/23

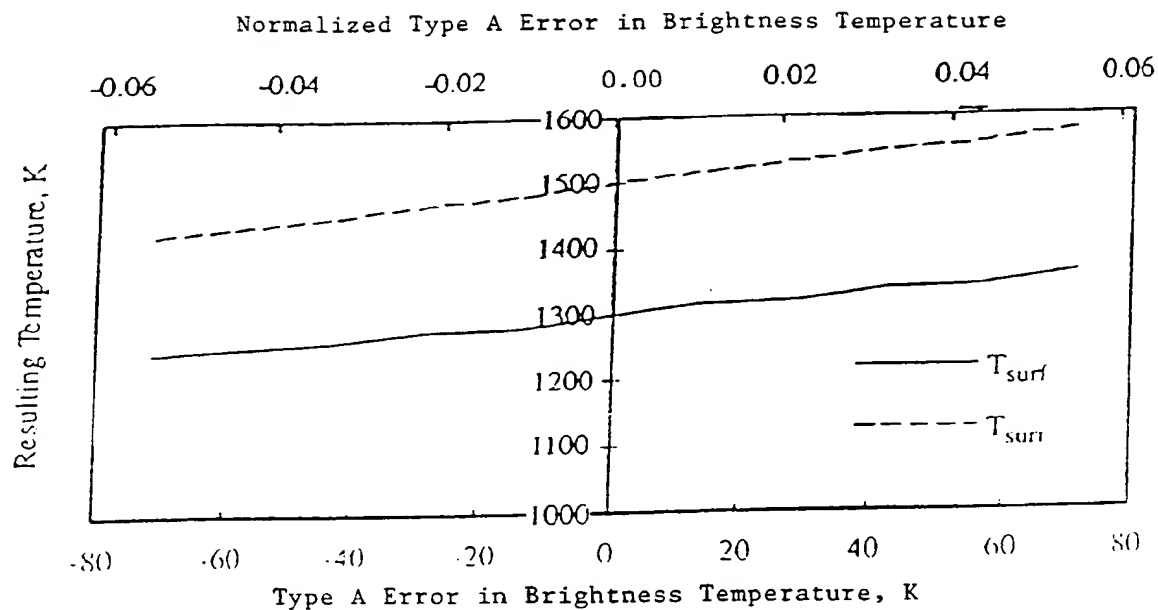


Figure 29A

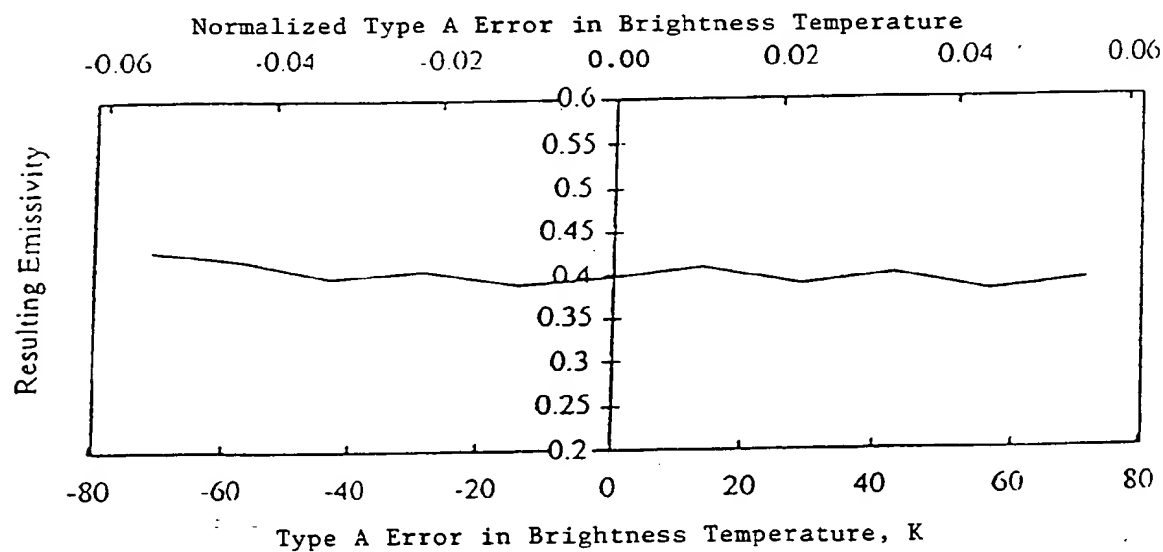


Figure 29

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23/23

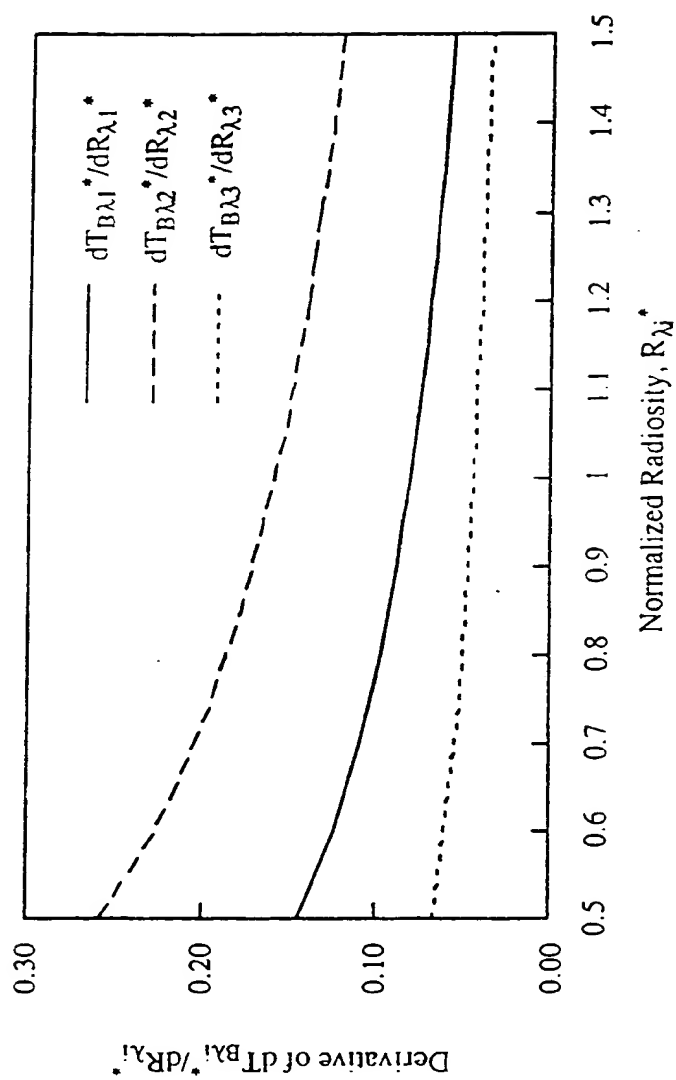


Figure 30

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US96/12008

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G01J 5/60, 1/00, 5/02; G01N 21/25

US CL : 356/43, 45, 418; 250/338.1, 339.04; 374/127; 437/247

According to International Patent Classification (IPC) or to both national classification and IPC \*

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/43, 45, 418; 250/338.1, 339.04; 374/127; 437/247

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

search: pyrometer, wavelength, wave length, multi?, plural?

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 5,165,796 (GAT ET AL), 24 NOVEMBER 1992, See col 1, line 60- col 2, line 5.	1-11
Y	US, A, 5,114,242 (GAT ET AL), 19 MAY 1992 See col 2, line 39 - col 3, line 15.	1-11
Y	US, A, 5,376,592 (HASHIGUCHI ET AL), 27 DECEMBER 1994, See col 3, line 45-54 and col 4, line 30-49.	1-11
A	US, A, 4,410,266 (SEIDER), 18 OCTOBER 1983, See whole document.	1-11
A	US, A, 4,880,314 (KIENITZ), 14 NOVEMBER 1989, See whole document.	1-11

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

## \* Special categories of cited documents:

\*A\* document defining the general state of the art which is not considered to be of particular relevance

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\*O\* document referring to an oral disclosure, use, exhibition or other means

\*P\* document published prior to the international filing date but later than the priority date claimed

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later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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\*Y\*

document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

\*&amp;\*

document member of the same patent family

Date of the actual completion of the international search

09 OCTOBER 1996

Date of mailing of the international search report

29 OCT 1996

Name and mailing address of the ISA/US  
Commissioner of Patents and Trademarks  
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Washington, D.C. 20231

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